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Philippe LORONG - Virtual machining Examples of numerical modelling Macroscopic and Mesoscopic scales - 2015

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Virtual machining

Examples of numerical modelling

Macroscopic and Mesoscopic scales

Philippe LORONG – Lab. PIMM at *Arts et Métiers ParisTech*

Team taking part in research on machining:

J. Duchemin, M. Guskov, P. Lorong

E. Balmes, G. Coffignal

L. Illoul, C. Gengembre

Main Industrial partners:

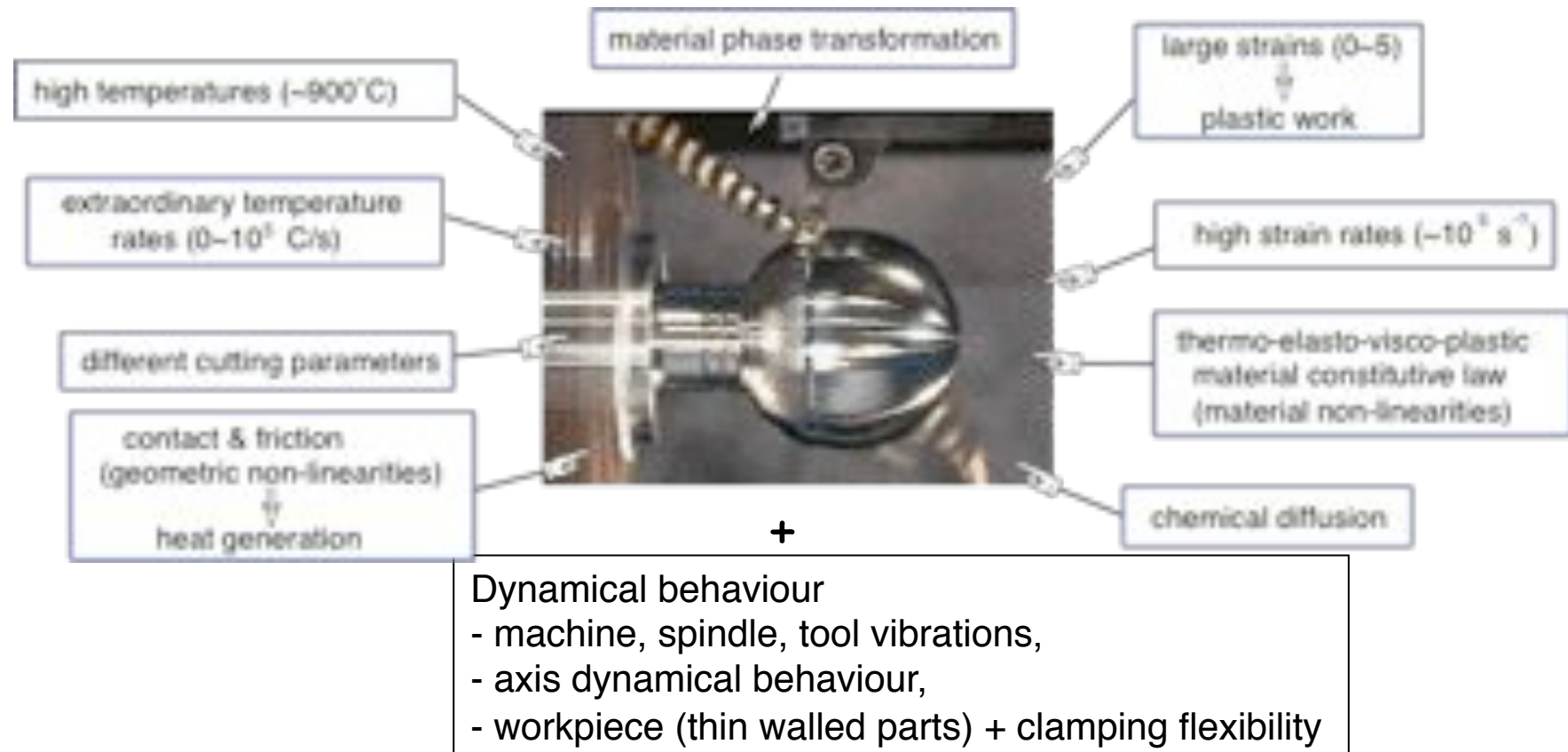
SAFRAN/Snecma : aeronautics (macroscopic scale)

PCI/PSC : automobiles and engine manufacturers (macroscopic scale)

Cetim: Technical center for the mechanical industry (macroscopic scale)

Modelling machining

Numerical simulation of metal cutting processes is particularly complex due to the diversity of the physical phenomena involved, a real challenge to existing algorithms and computational tools



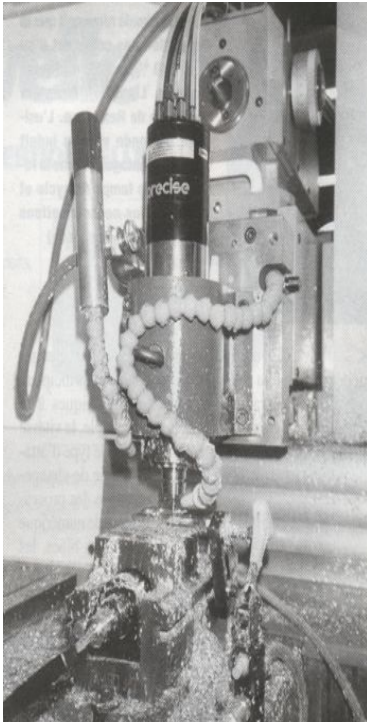
*Its difficult to reproduce
all the phenomenon in a single simulation*



Multi-scale approach

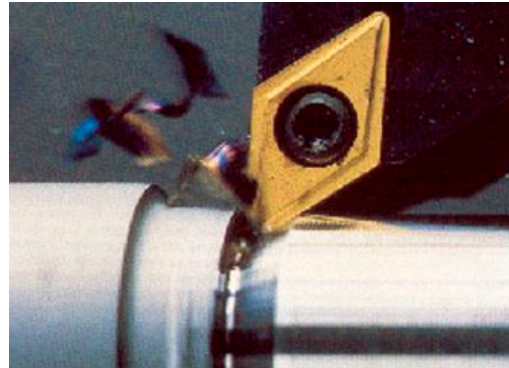
The different scales

Macroscopic



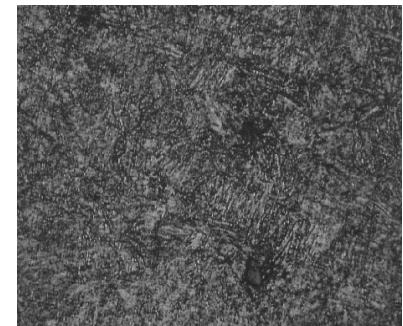
The whole
Workpiece-Tool-
Machine system

Mesososcopic



The
neighbourhood
of the tool tip

Microscopic



Grains of the
mater

Macroscopic scale

System

Workpiece/Tool/Machine

Objectives

Machining system dynamics
Geometry of the machined surface
(form, waviness, roughness defects)
Cutting forces, power (history of ...)

Mechanical context

Nonlinear dynamics
Small strains
Known large displacement



Milling / Turning

Flexible Part

Mesososcopic scale

System

Neighbourhood of the Tool tip

Objectives

Matter separation/Chip formation
Thermo-mechanical solicitations
applied on :
- the tool (tool wear)
- the workpiece (surface integrity)

Mechanical context

Nonlinear thermo-mechanics with
large displacement and large strains
multi-physics



Blanking / Cutting

C-Nem

Research at PiMM Laboratory

Macroscopic scale

System

Workpiece/Tool/Machine

Objectives

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Geometry of the machined surface
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Research at PiMM Laboratory

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Flexible Part

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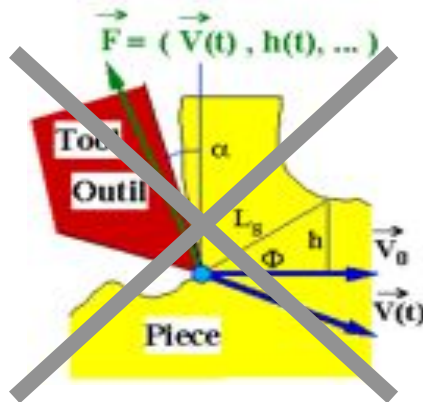


Blanking / Cutting

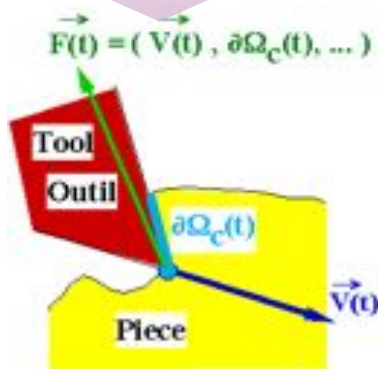
C-Nem

Macroscopic scale : Tool/Part interaction model

→ Chip formation is not modelled



The tool erase the mater

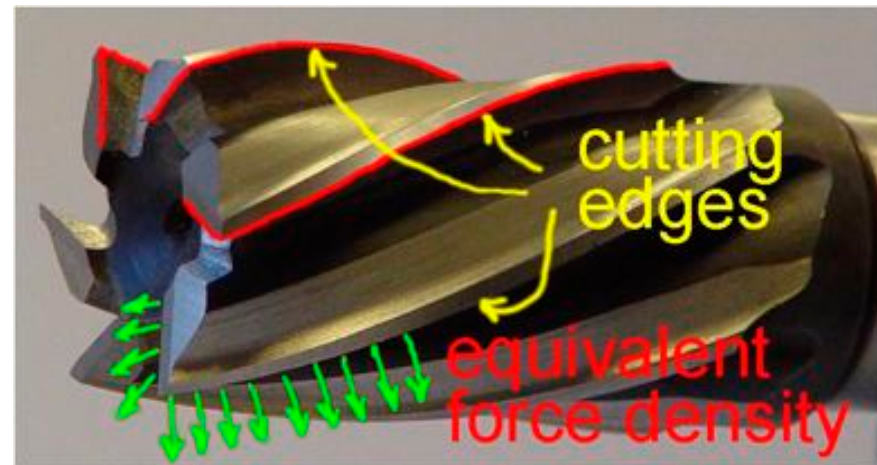


Cutting forces are deduced from:

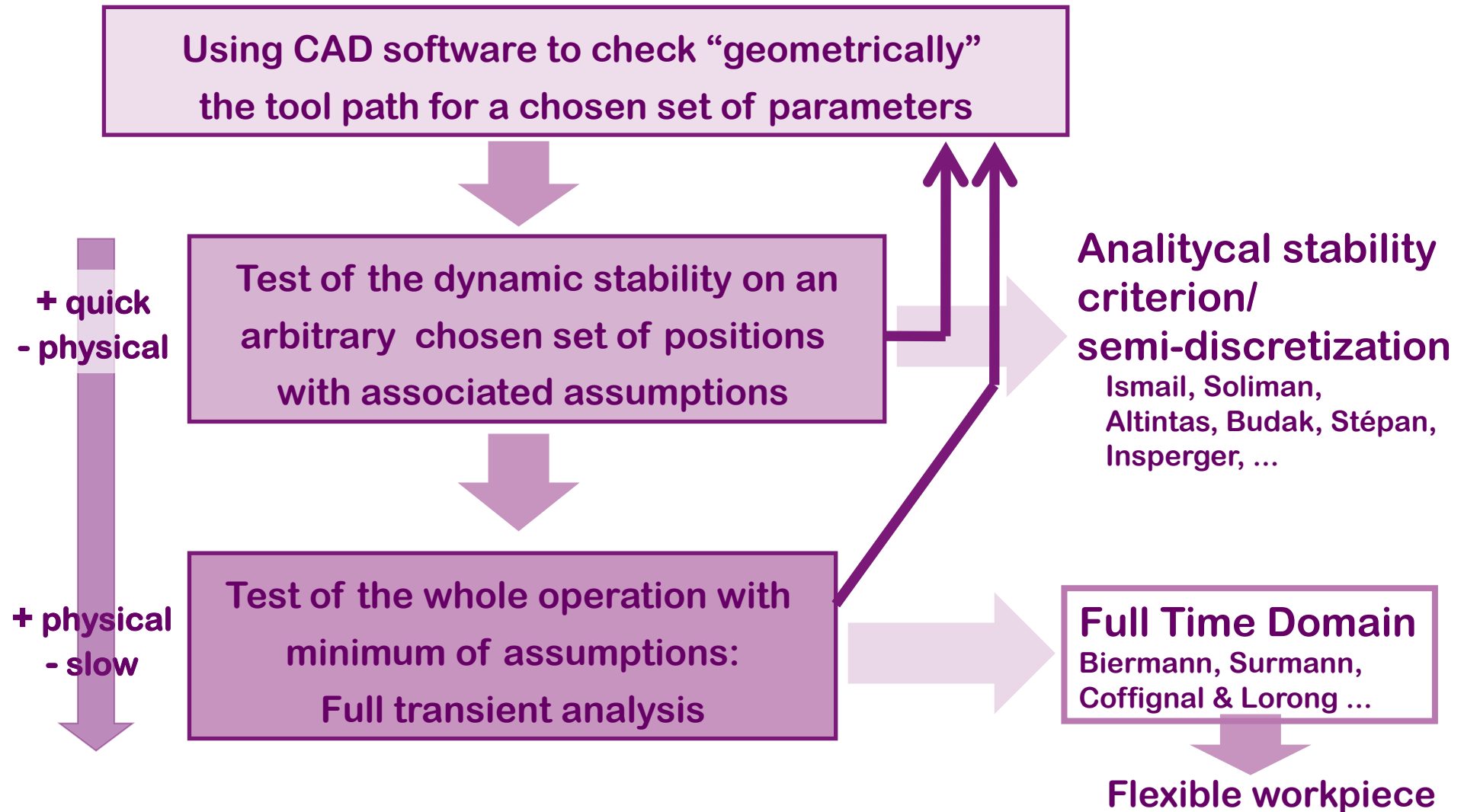
- instantaneous cutting conditions
- a cutting law

Typical cutting law:

$$F_{\alpha} = K_{\alpha} \frac{b}{h_0} \left(\frac{h}{h_0} \right)^{n_{\alpha}}$$

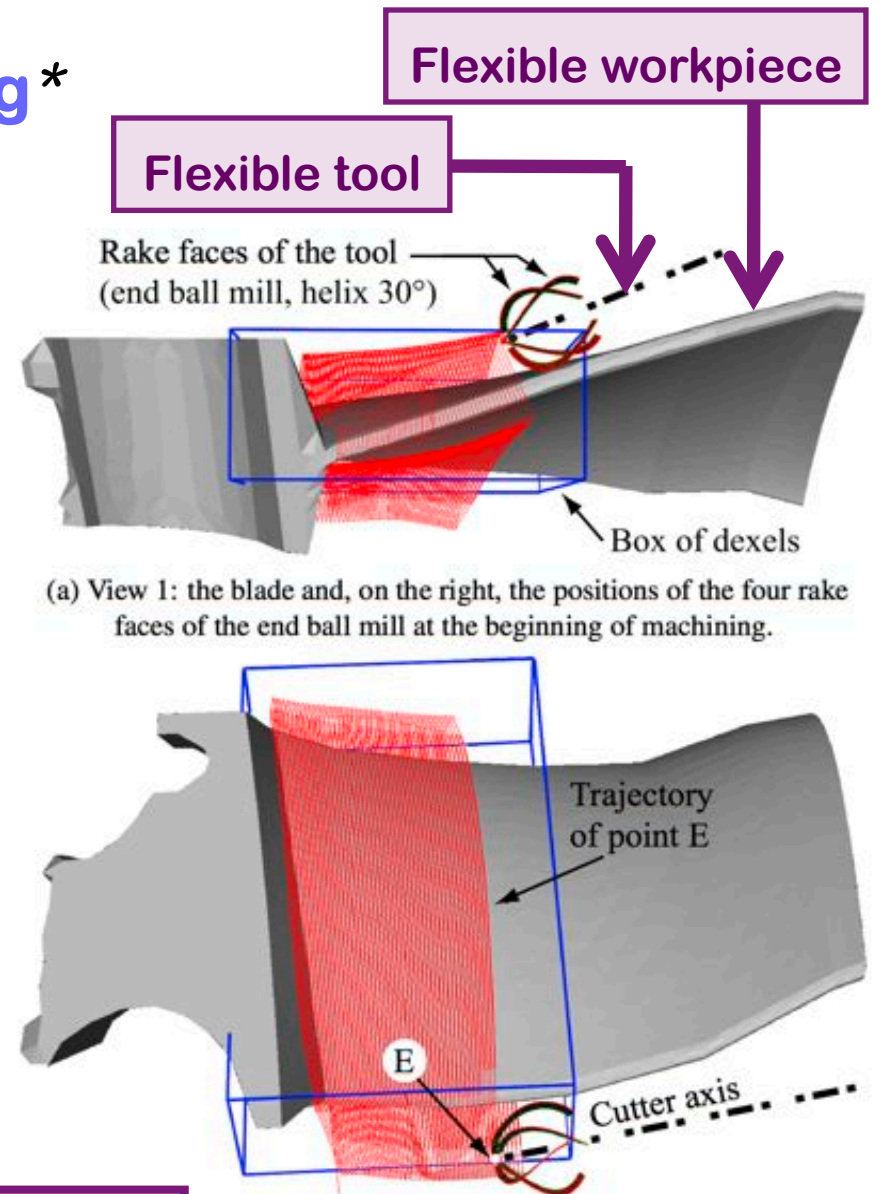
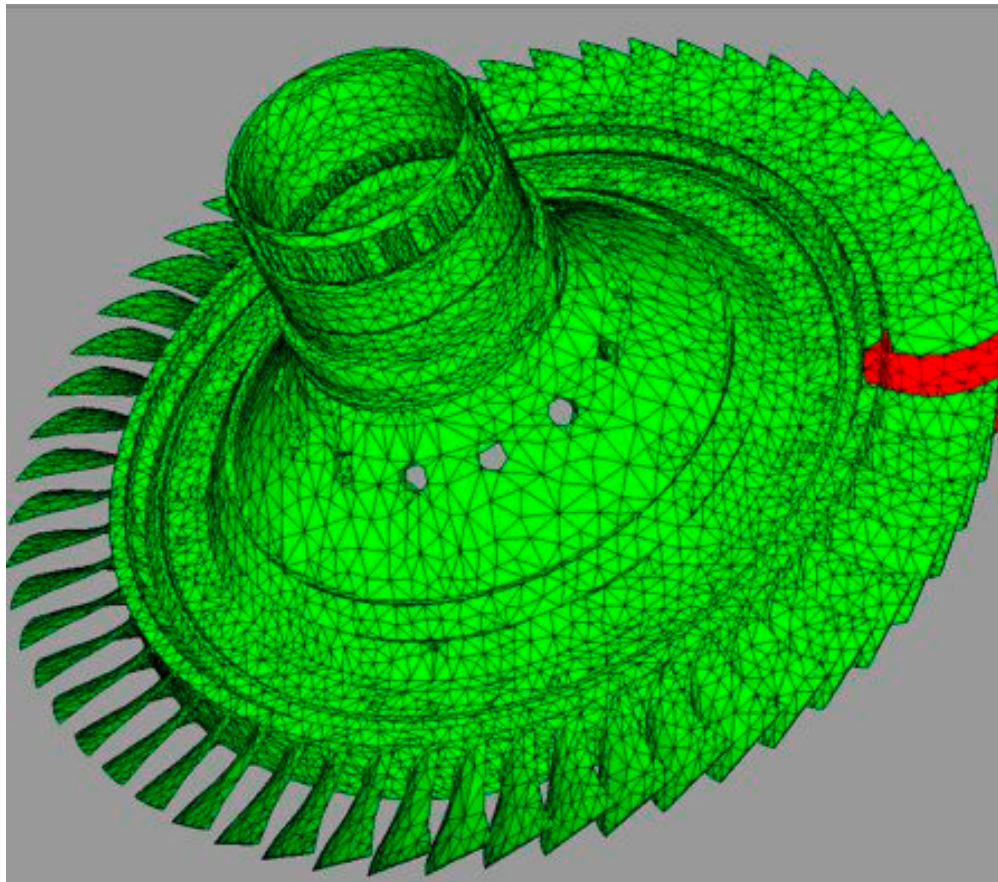


Approaches at the macroscopic scales



A typical example: Blade milling *

Bladed disc (blisc) : 56 blades



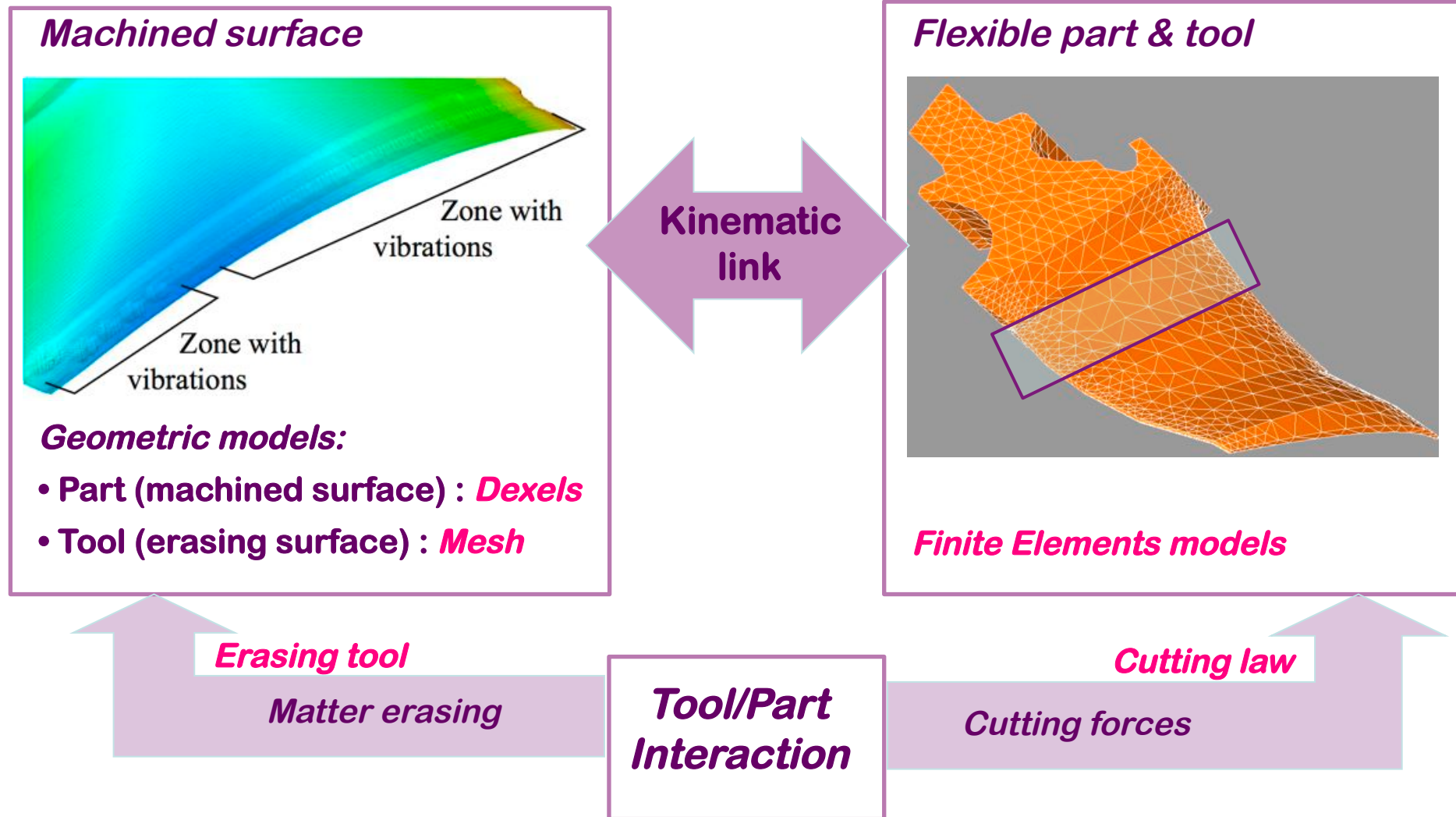
(a) View 1: the blade and, on the right, the positions of the four rake faces of the end ball mill at the beginning of machining.

Tool and Workpiece may be flexible

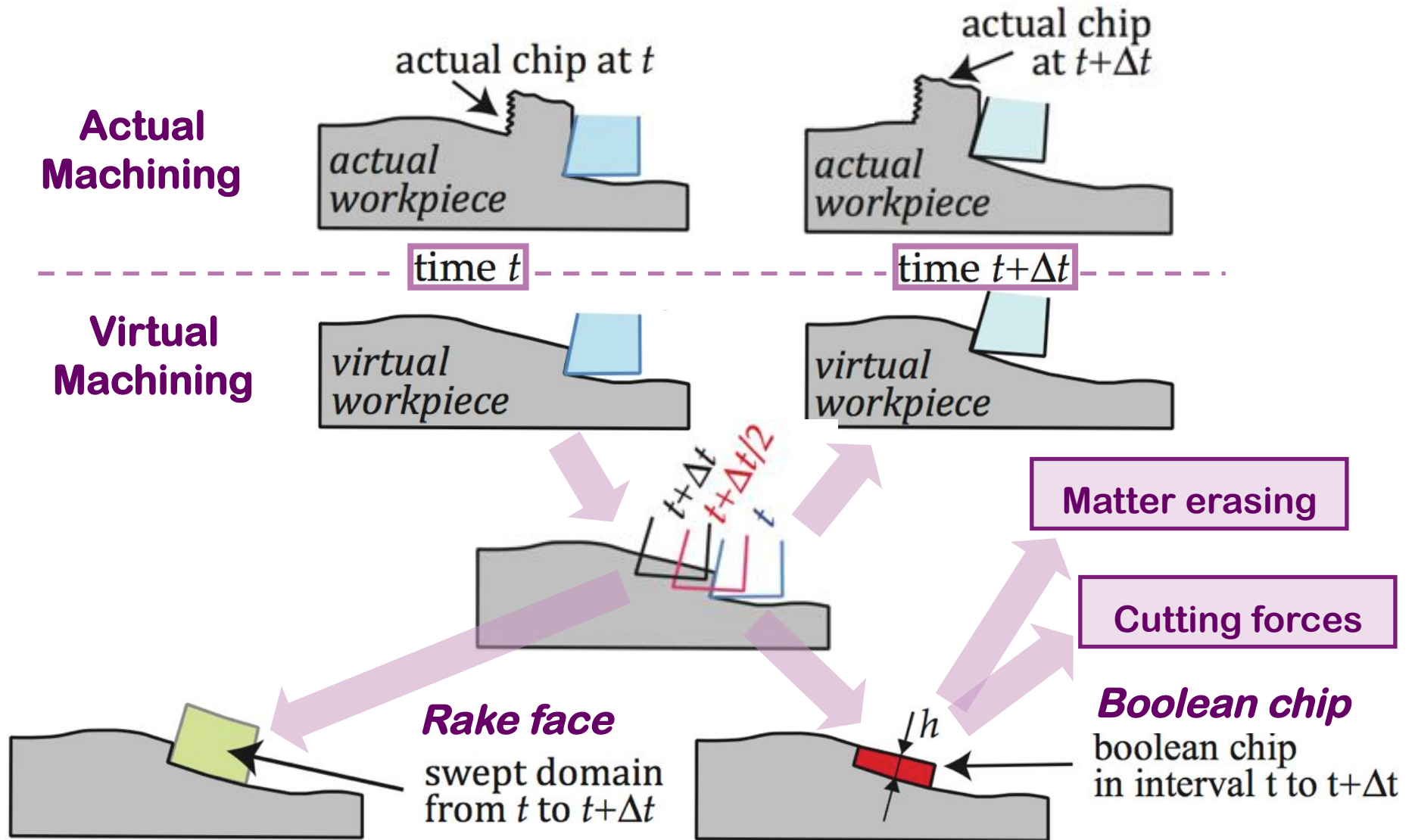
imposed trajectory of the center point of the cutter end E , and the positions of the four rake faces at $\tau = 0$.

Needed models

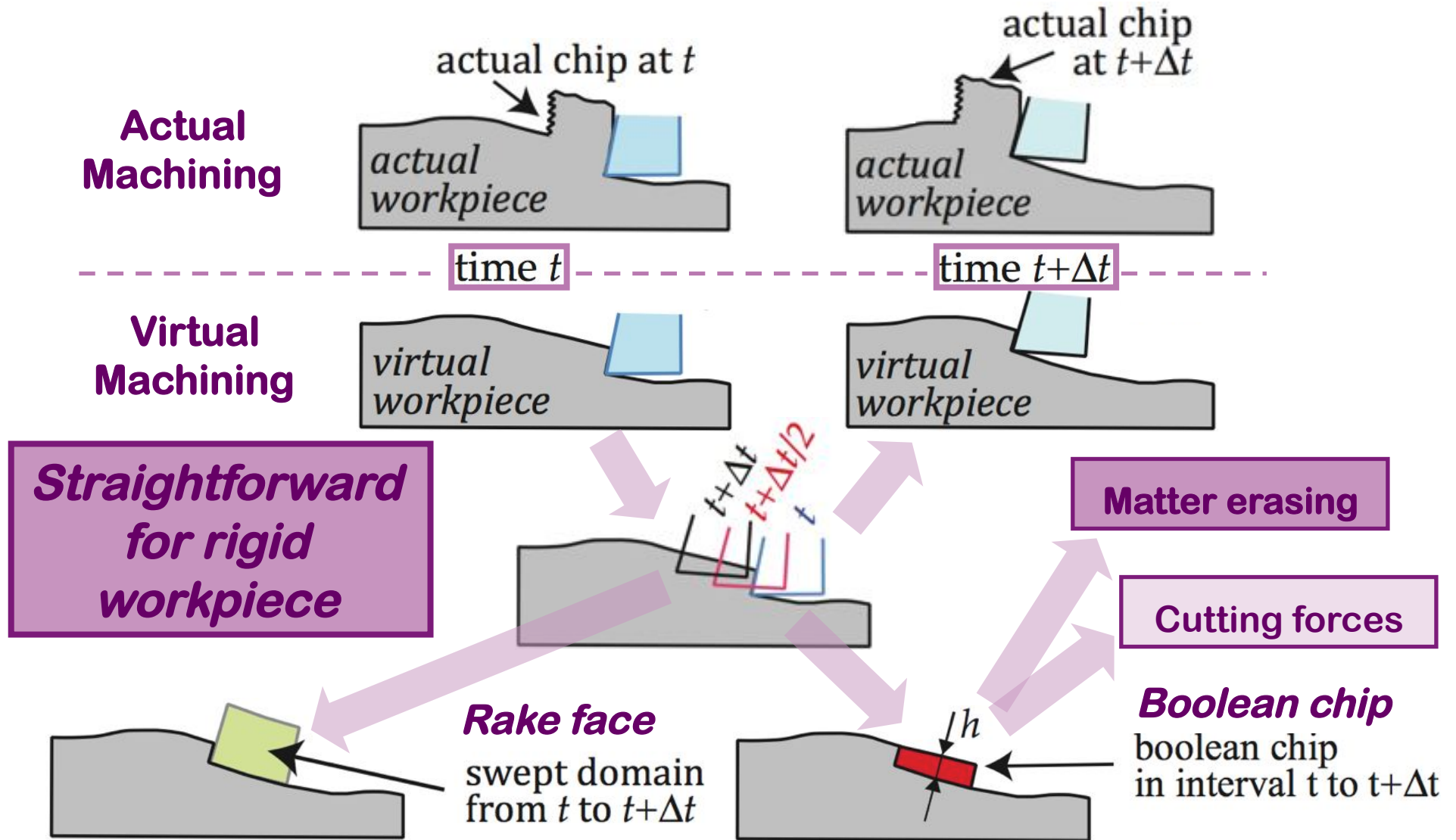
→ The FE cannot be used to model the matter erasing



Tool/Workpiece interaction – Rigid workpiece



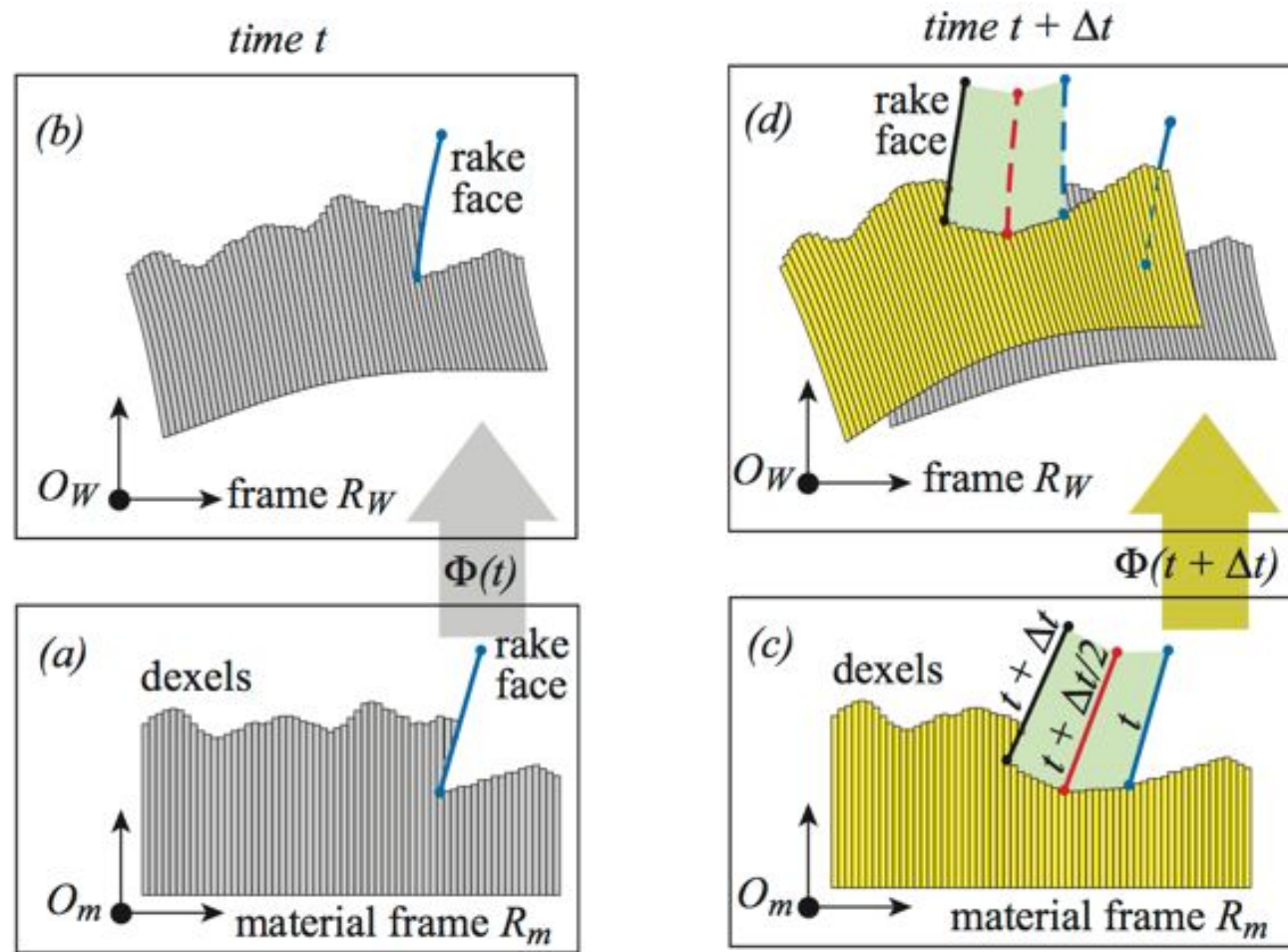
Tool/Workpiece interaction – Rigid workpiece



Tool/Workpiece interaction – Flexible workpiece

Shape of
the workpiece
in R_W

Shape of
the workpiece
in R_m

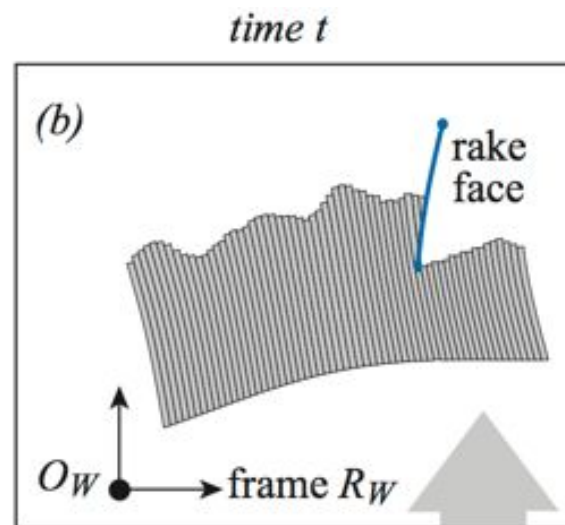


R_W : frame where dynamic model of the workpiece is defined

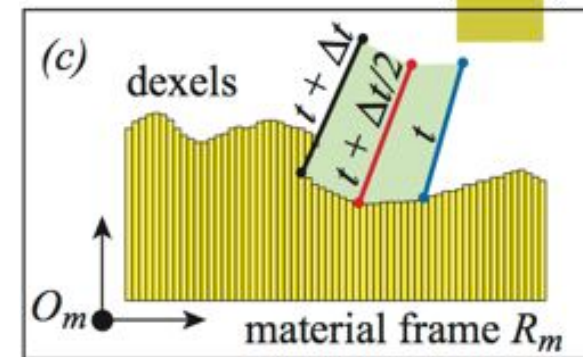
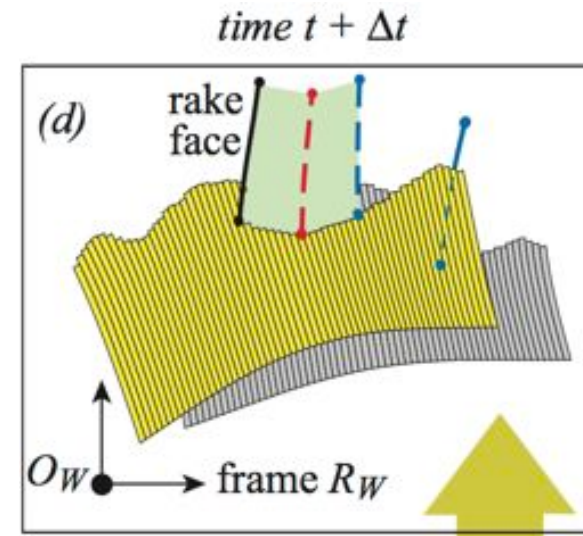
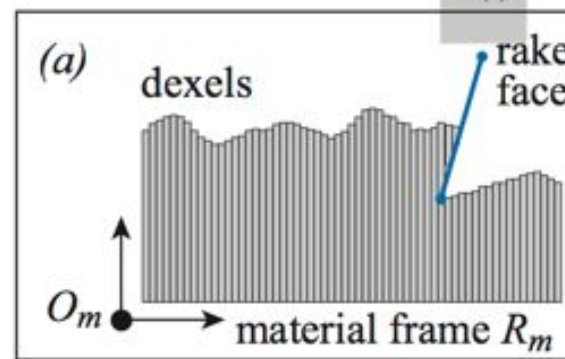
R_m : material frame of the workpiece

Tool/Workpiece interaction – Flexible workpiece

Shape of
the workpiece
in R_W

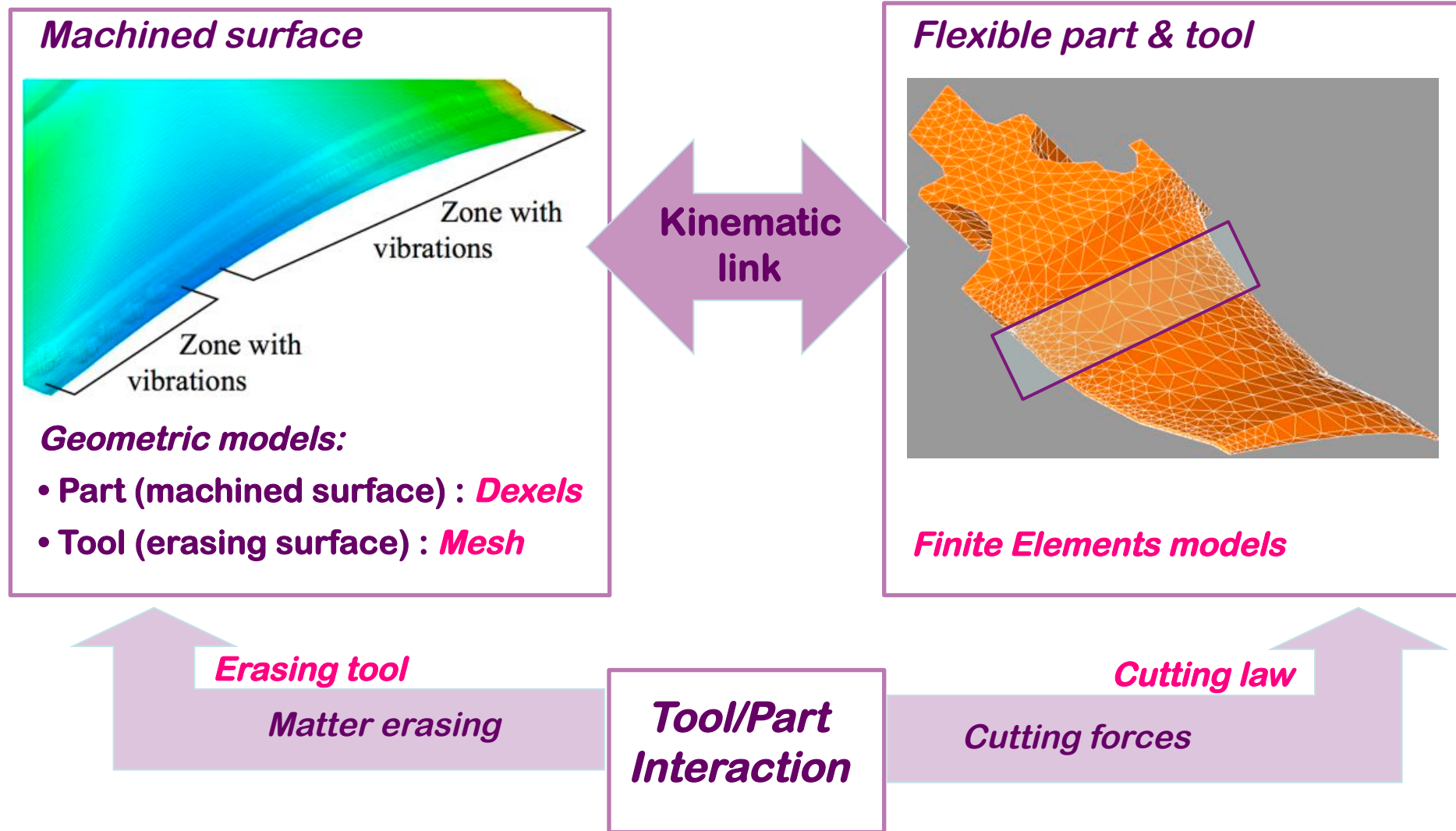


Shape of
the workpiece
in R_m



**Matter erasing is conducted
in the material frame R_m**

Needed models



Blisc Flexible part & tool: Finite Elements Models

The workpiece

Simulations with a single blade:

- Quadratic tetrahedrons
➡ first 10 mode shapes

Simulation with the whole Blisc:

- Quadratic tetrahedrons + cyclic symmetry
➡ first 180 mode shapes

$$\begin{cases} [M]_T \cdot \{\ddot{q}\}_T + [\tilde{D}]_T \cdot \{\dot{q}\}_T + [\tilde{K}]_T \cdot \{q\}_T = \{Q\}_T + \{Q\}_{W/T} \\ [M]_W \cdot \{\ddot{q}\}_W + [\tilde{D}]_W \cdot \{\dot{q}\}_W + [\tilde{K}]_W \cdot \{q\}_W = \{Q\}_W + \{Q\}_{T/W} \end{cases}$$

➡ Include non Galilean effects (rotations,...)

➡ A modal reduction is used

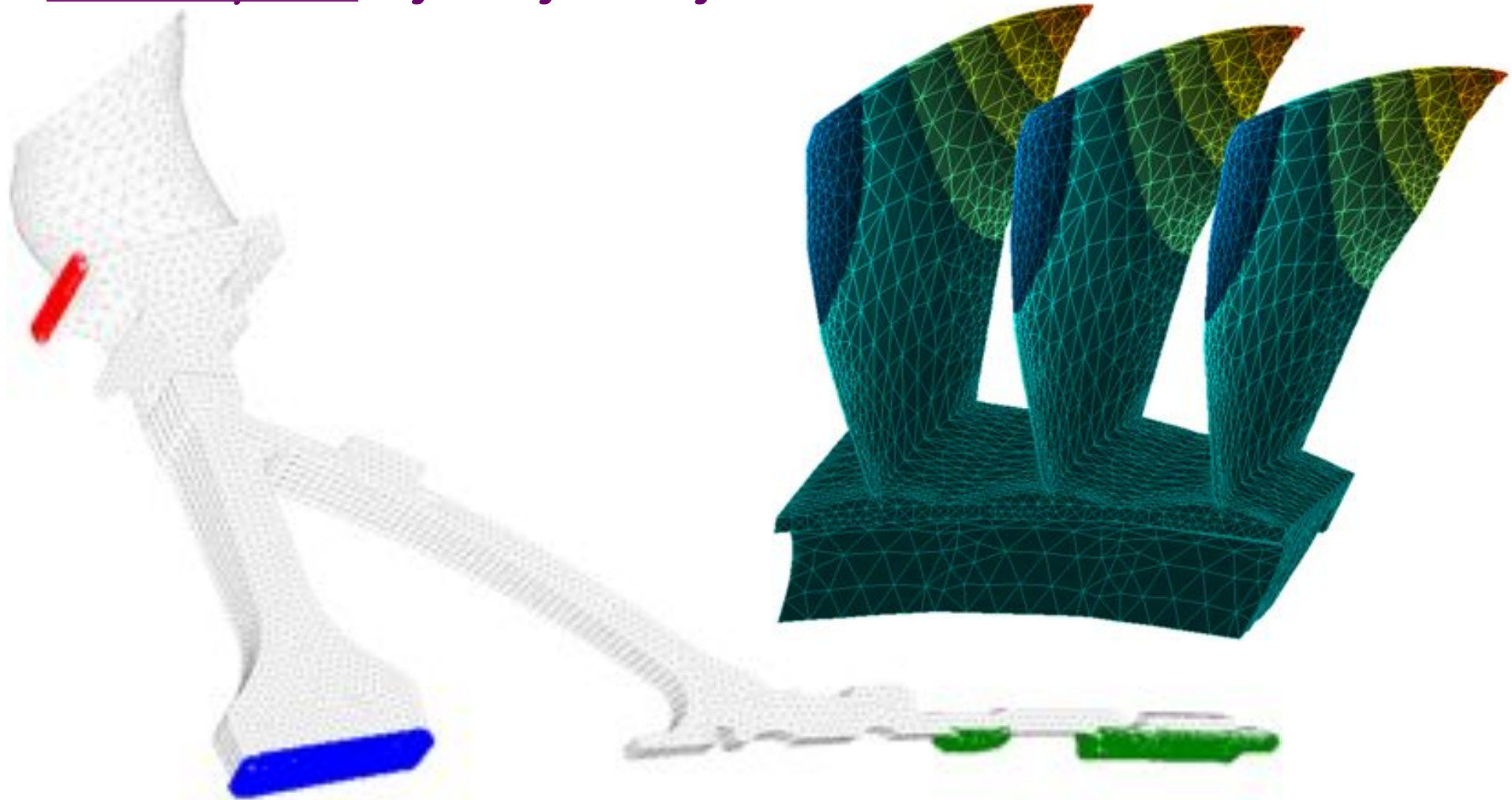
The tool

➡ A Simple beam
(rake faces
having a rigid
motion)

Cutting forces

Flexible part: **Finite Elements Model**

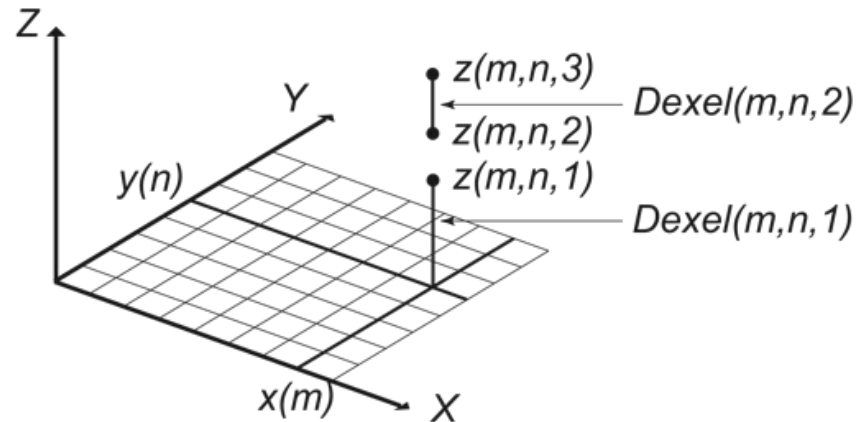
The workpiece: Cyclic symmetry



Modelling: SDT (Structural Dynamic Toolbox)

Geometric model of the machined area

Dexel-based volume representation (multi-level Z-Map model*)



Fine (but non homogeneous)

➡ Necessary to describe the matter erasing and cutting forces

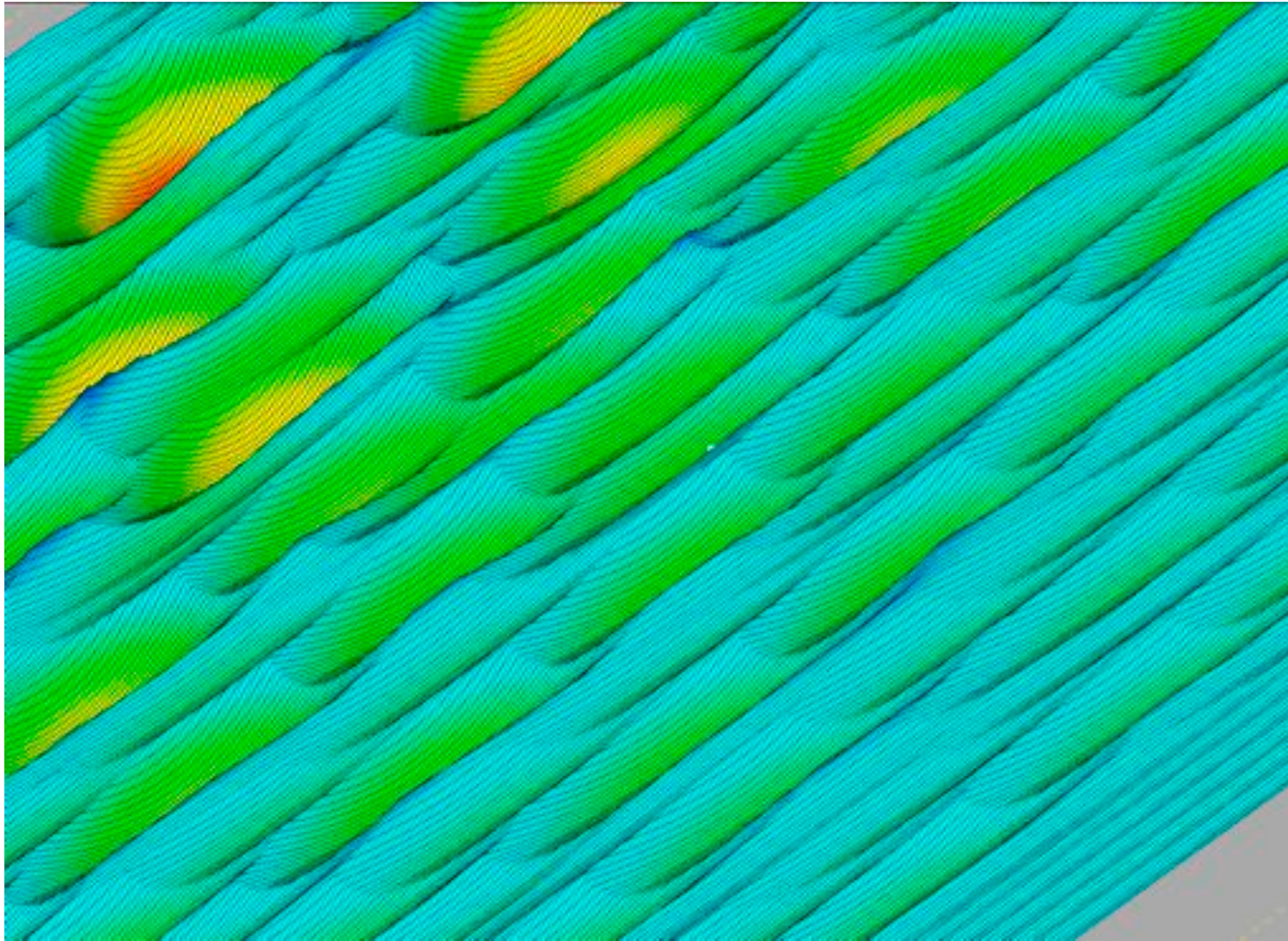
Intersection algorithms are robust

➡ Necessary for the Time Domain approach (nb Time steps $\sim 10^6$)

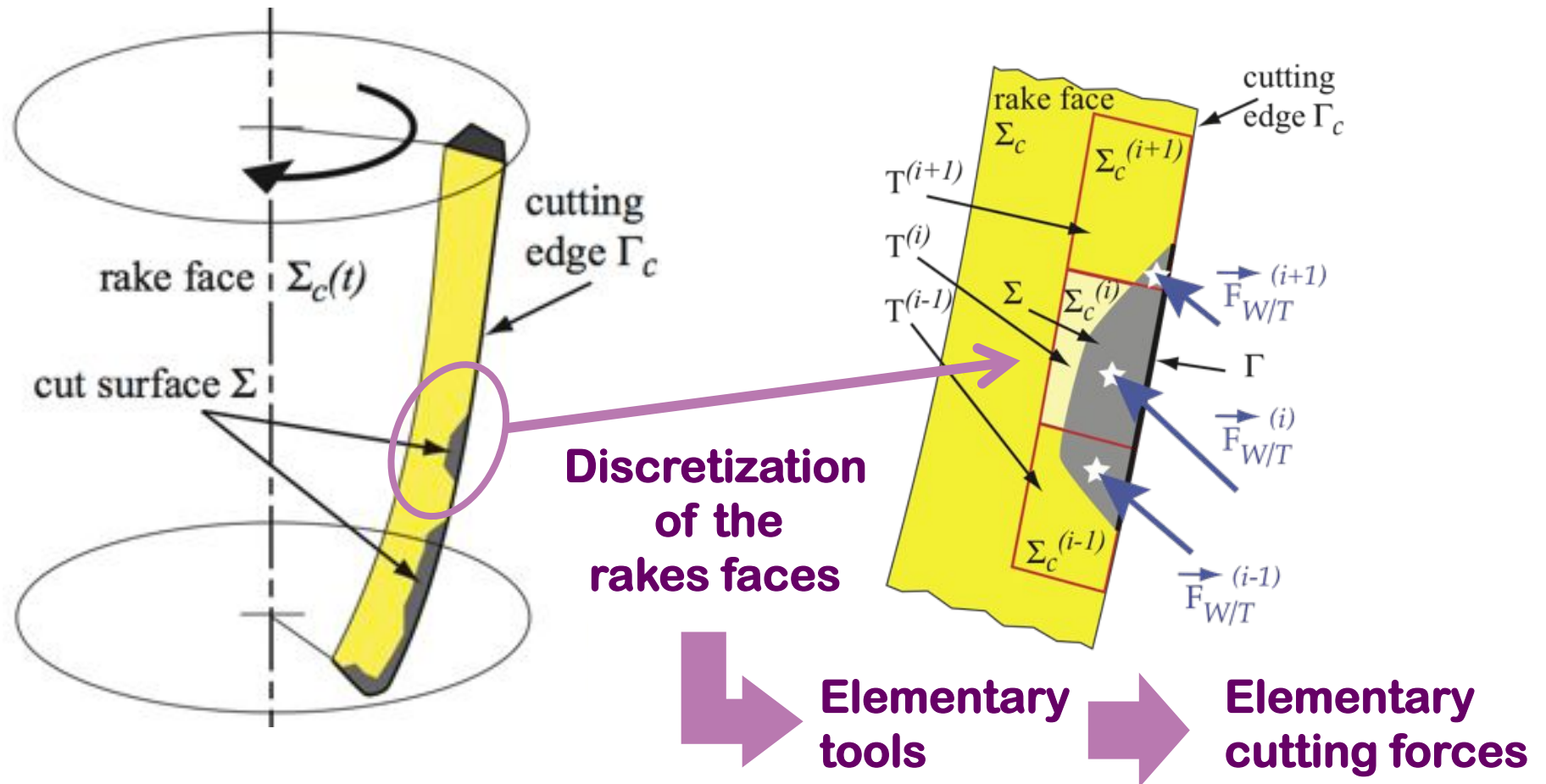
* B.K. Choi and R.B. Jerard

Geometric model of the machined area

Example of a machined surface describes with dexels (20 000 000)



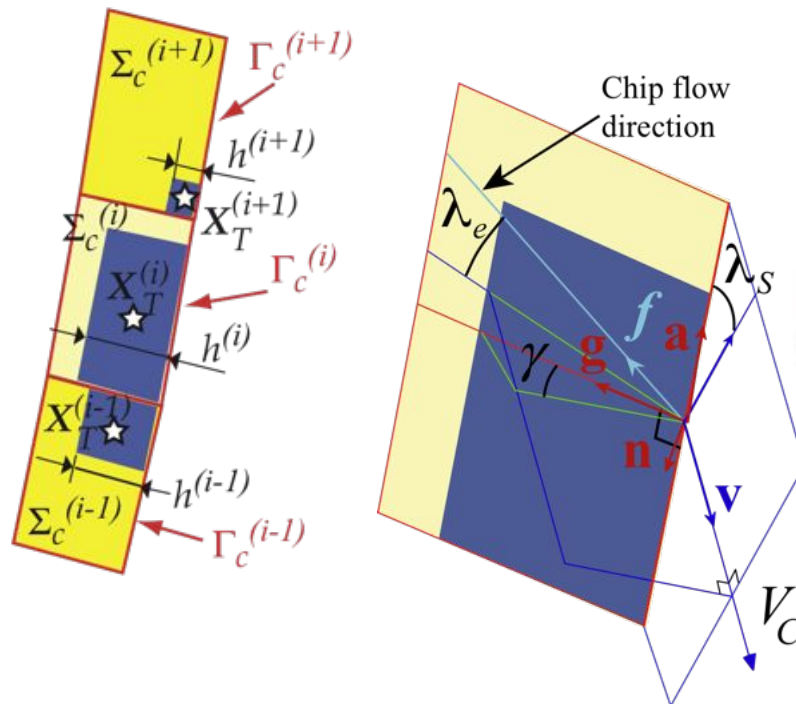
Tool/Part interaction: *Cutting forces – Cutting law*



Tool/Part interaction: Cutting forces

Elementary cutting forces

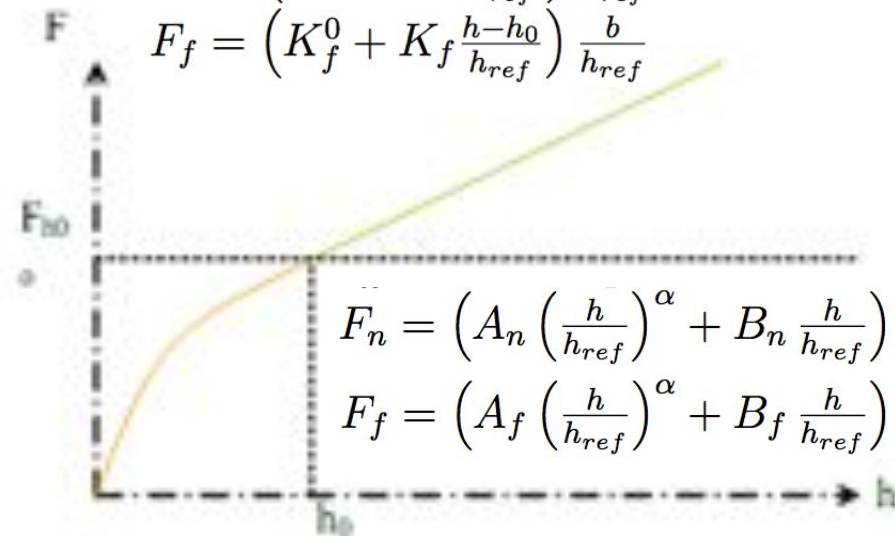
Cutting law*



$$\lambda_e = K_{\lambda_e} \cdot \lambda_s$$

$$F_n = \left(K_n^0 + K_n \frac{h-h_0}{h_{ref}} \right) \frac{b}{h_{ref}}$$

$$F_f = \left(K_f^0 + K_f \frac{h-h_0}{h_{ref}} \right) \frac{b}{h_{ref}}$$



$$F_n = \left(A_n \left(\frac{h}{h_{ref}} \right)^\alpha + B_n \frac{h}{h_{ref}} \right) \frac{b}{h_{ref}}$$

$$F_f = \left(A_f \left(\frac{h}{h_{ref}} \right)^\alpha + B_f \frac{h}{h_{ref}} \right) \frac{b}{h_{ref}}$$

$$A_n = \frac{K_n^0 - \frac{h_0}{h_{ref}} K_n}{(1-\alpha) \left(\frac{h_0}{h_{ref}} \right)^\alpha} \quad B_n = K_n - \alpha \left(\frac{h_0}{h_{ref}} \right)^{\alpha-1} A_n$$

$$A_f = \frac{K_f^0 - \frac{h_0}{h_{ref}} K_f}{(1-\alpha) \left(\frac{h_0}{h_{ref}} \right)^\alpha} \quad B_f = K_f - \alpha \left(\frac{h_0}{h_{ref}} \right)^{\alpha-1} A_f$$

*N. Corduan, PHD

Headlines of the Algorithm

Dynamic non linear time domain approach

Newmark Incremental Scheme

+ Newton Iterations Scheme for each time-step

On an increment (from t to $t+\Delta t$)

- *For each iteration:*

1. Calculation of the Cutting forces



Intersection between :

- *actual domain* occupied by the workpiece
- *swept volume* generated by the rake faces over *the increment*

2. Evaluation of the dynamical balance

- *When the Newton scheme has converged:*

Updating of the Workpiece Geometry Model

The numerical cost is mainly due to the intersection calculations

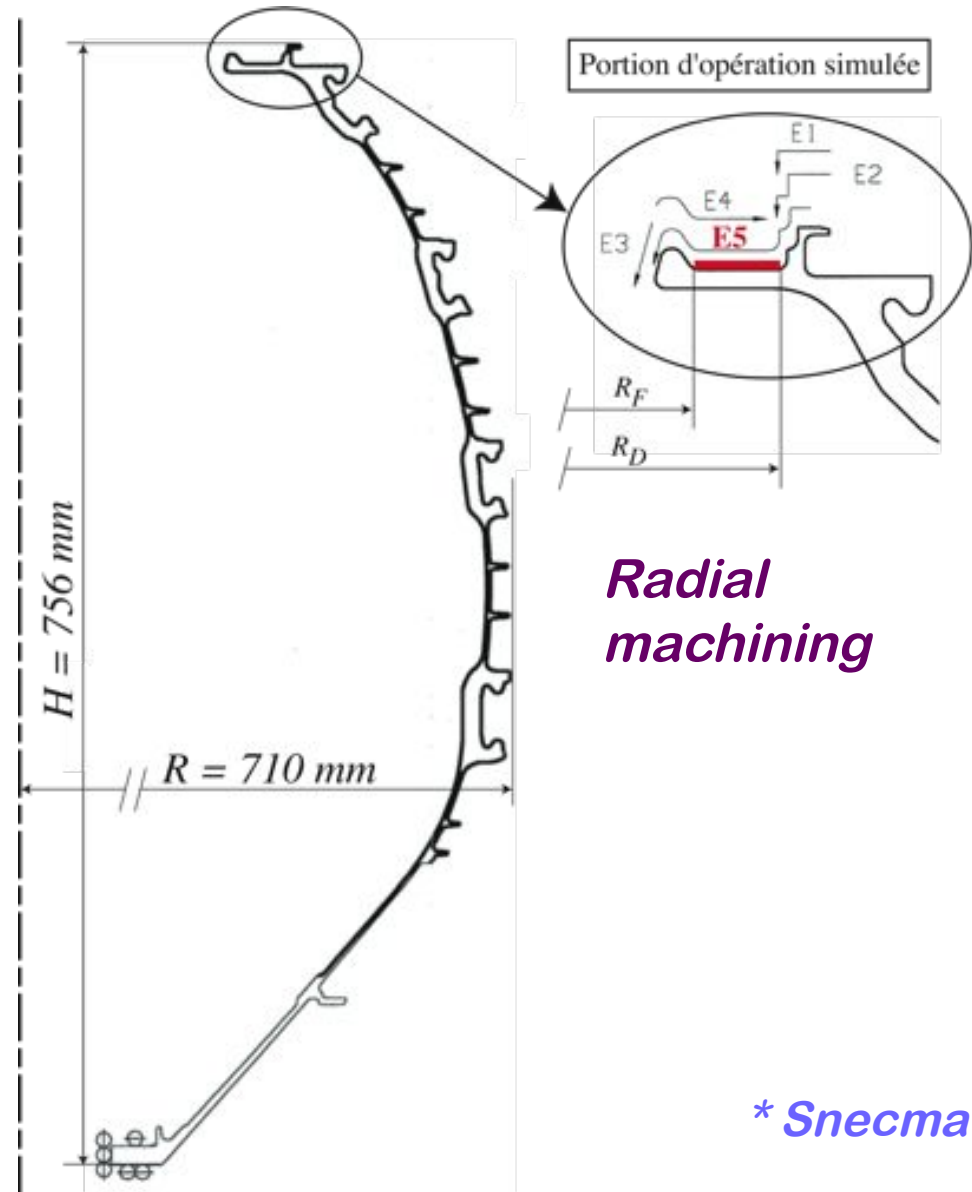
Turning example: Drum (turbofan GE90 engine*)

FE model of the Drum



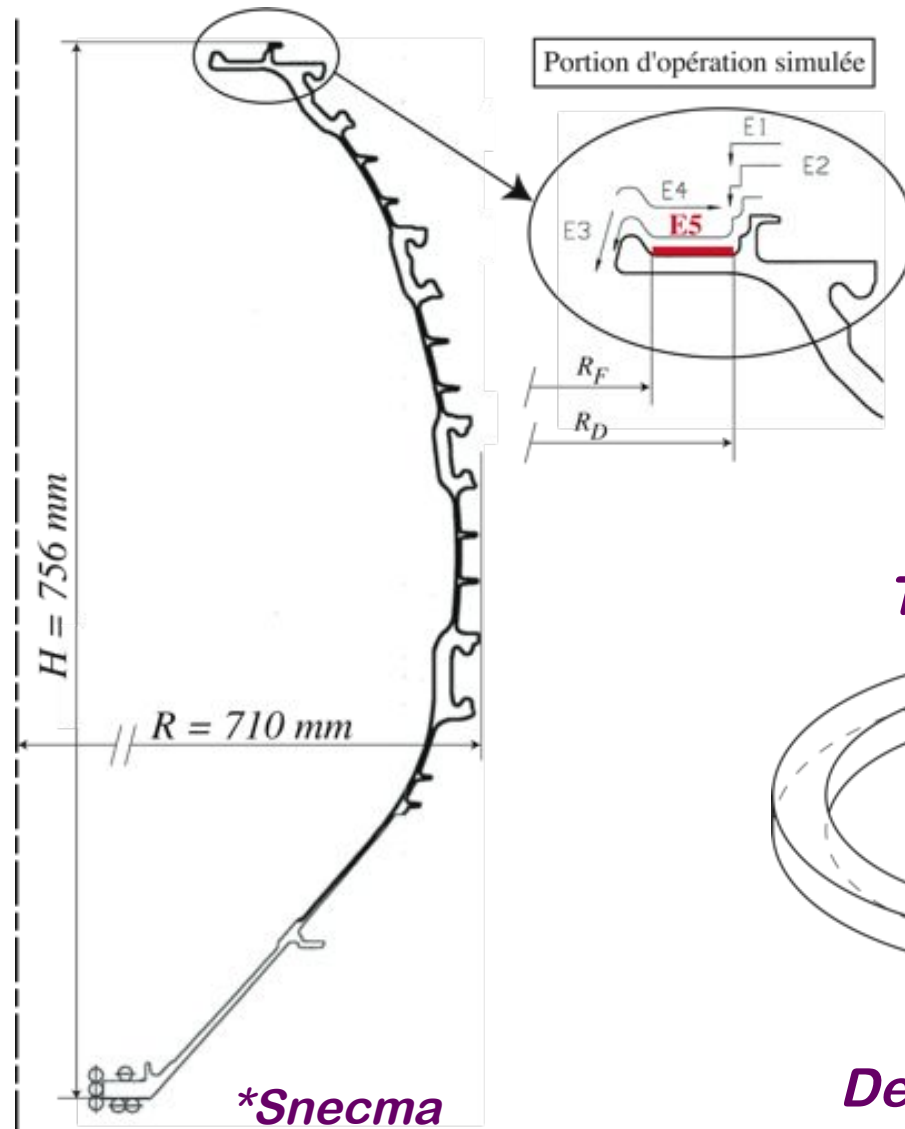
- expensive part
- lack of experimental data

Development of
a laboratory
experiment

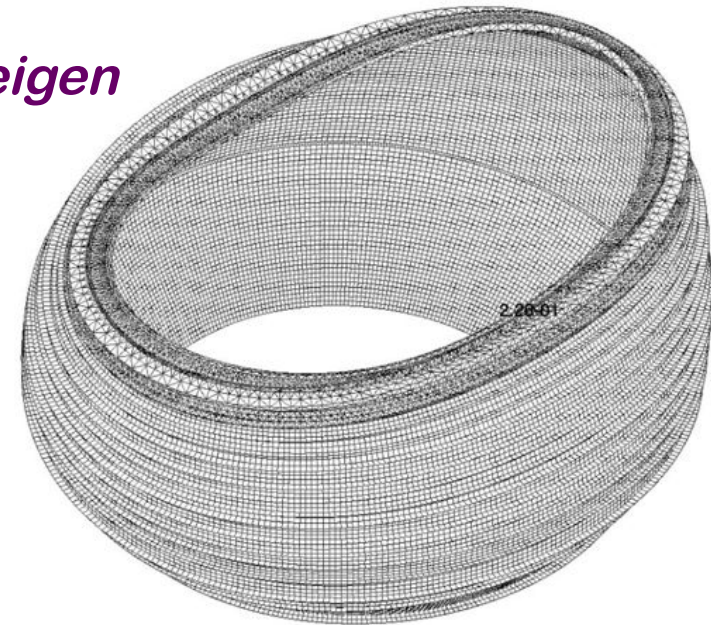


* Snecma

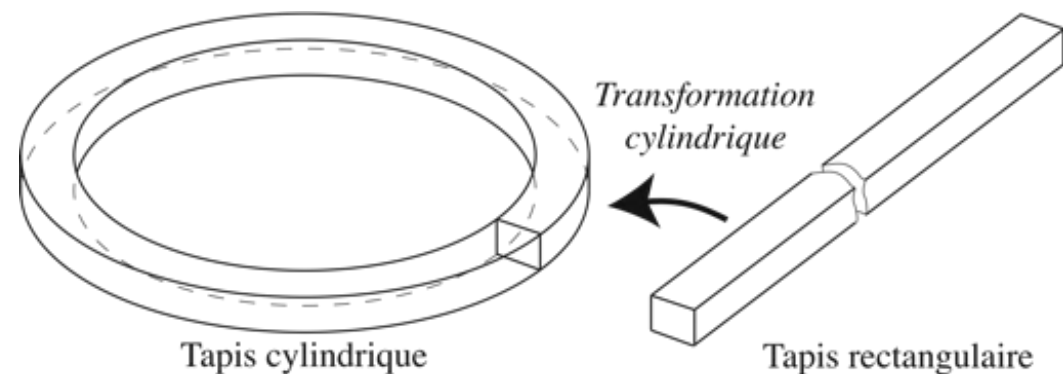
Back to the drum (turbofan GE90 engine)*



First eigen mode



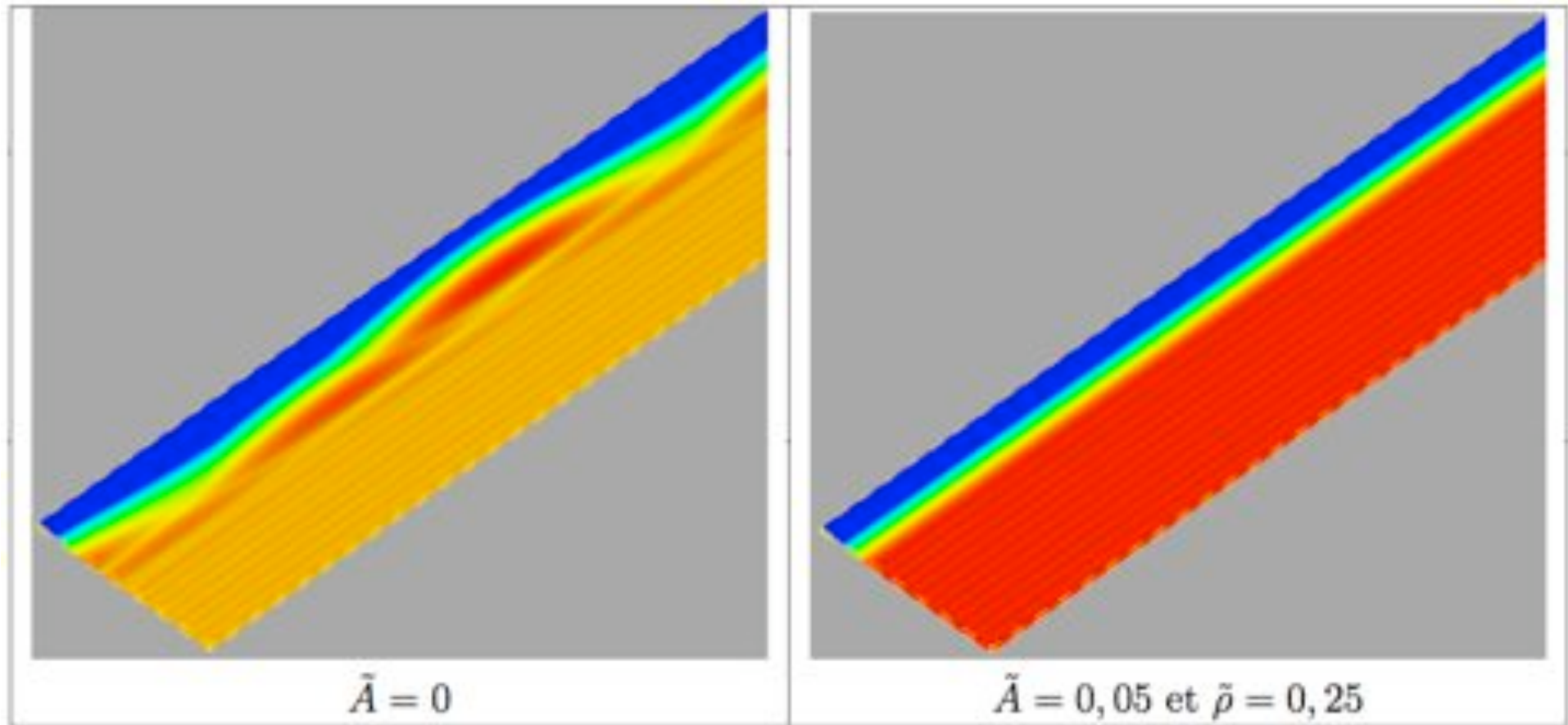
Transformation of the dixel carpet



Dexels are put in the axial direction

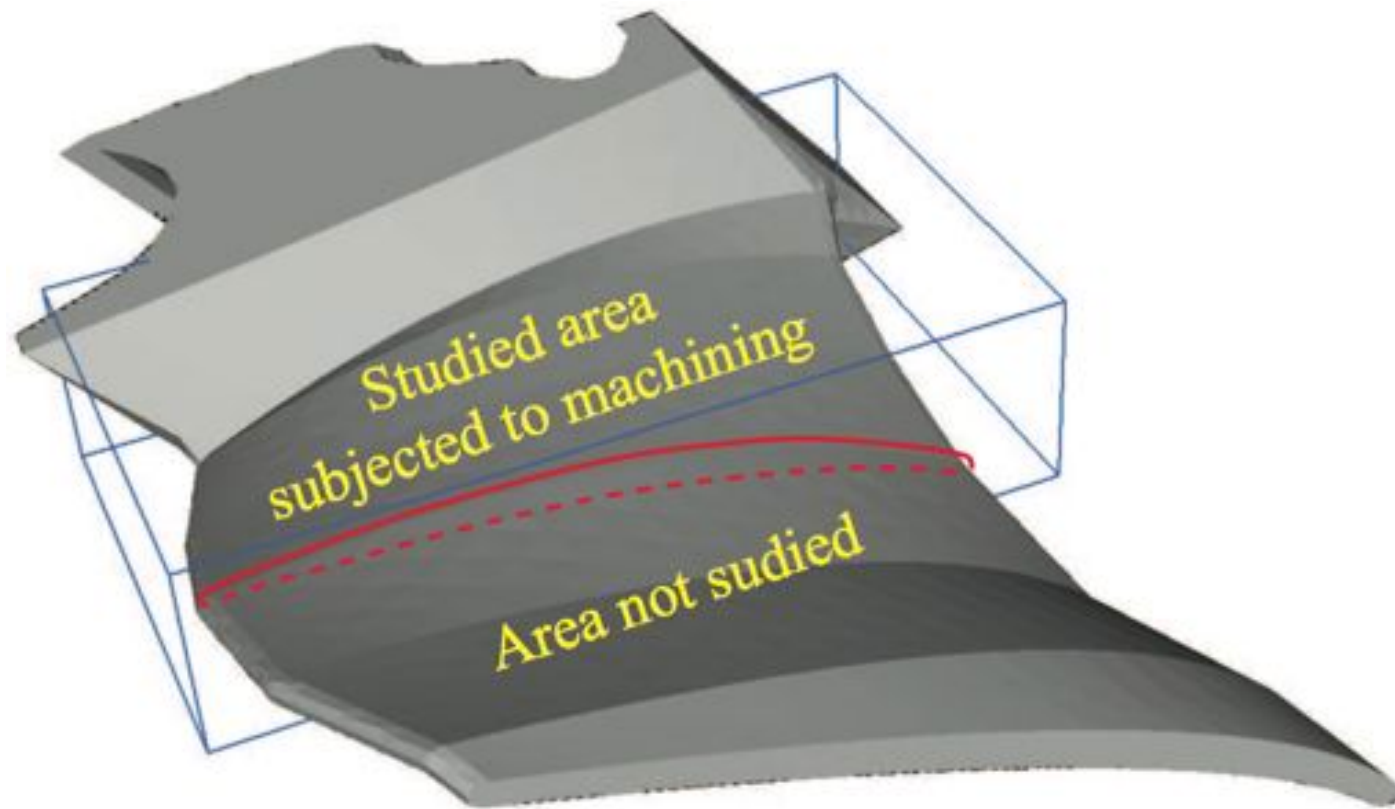
Back to the drum (turbofan GE90 engine)*

Effect of the modulation of the cutting speed



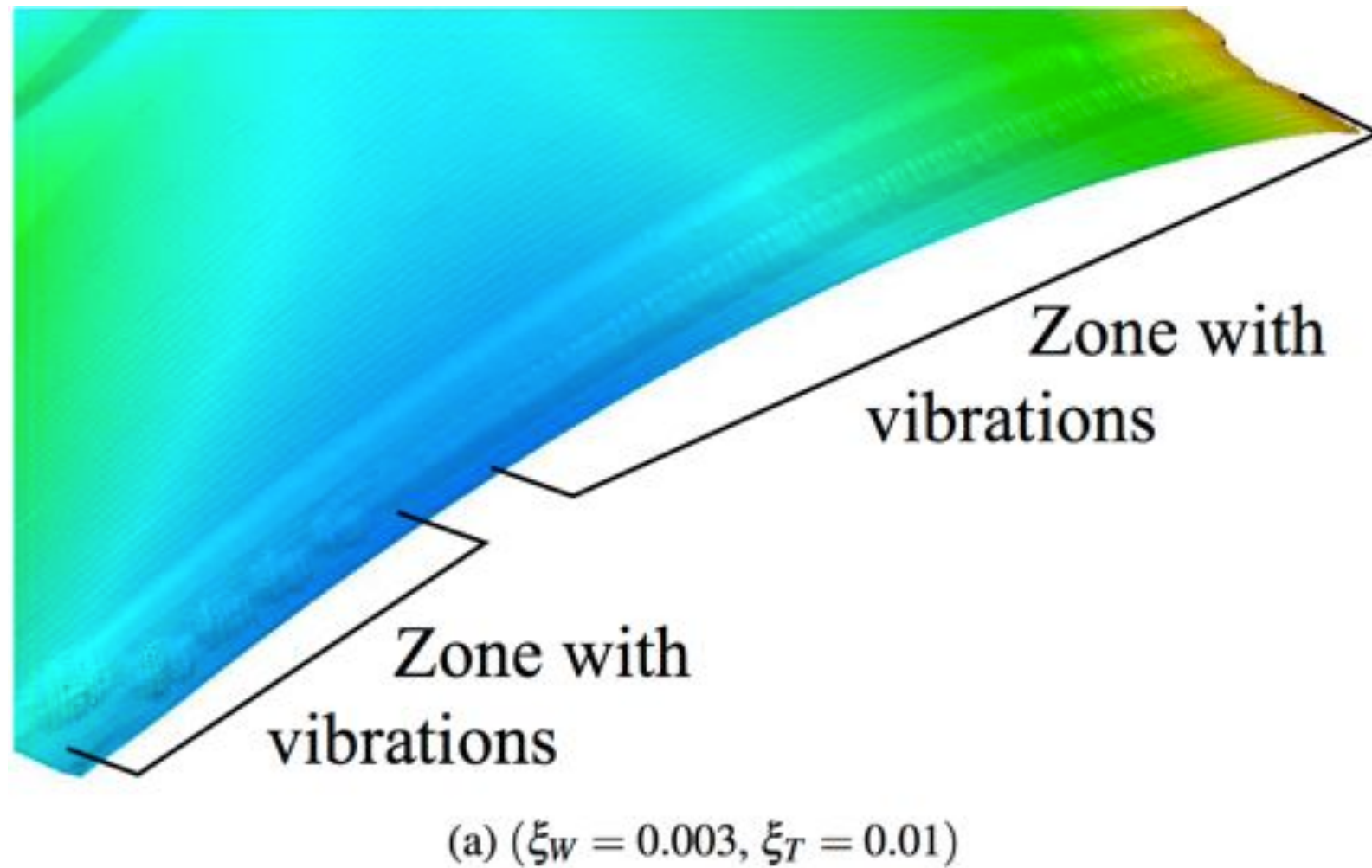
$$\tau = 0,44\% \quad \tilde{V}_c(t) = V_c * \left[1 + \tilde{A} * \sin(\tilde{\omega}t) \right] \quad \tilde{\rho} = \frac{\tilde{\omega}}{\omega_{broche}}$$

Blisc simulation results



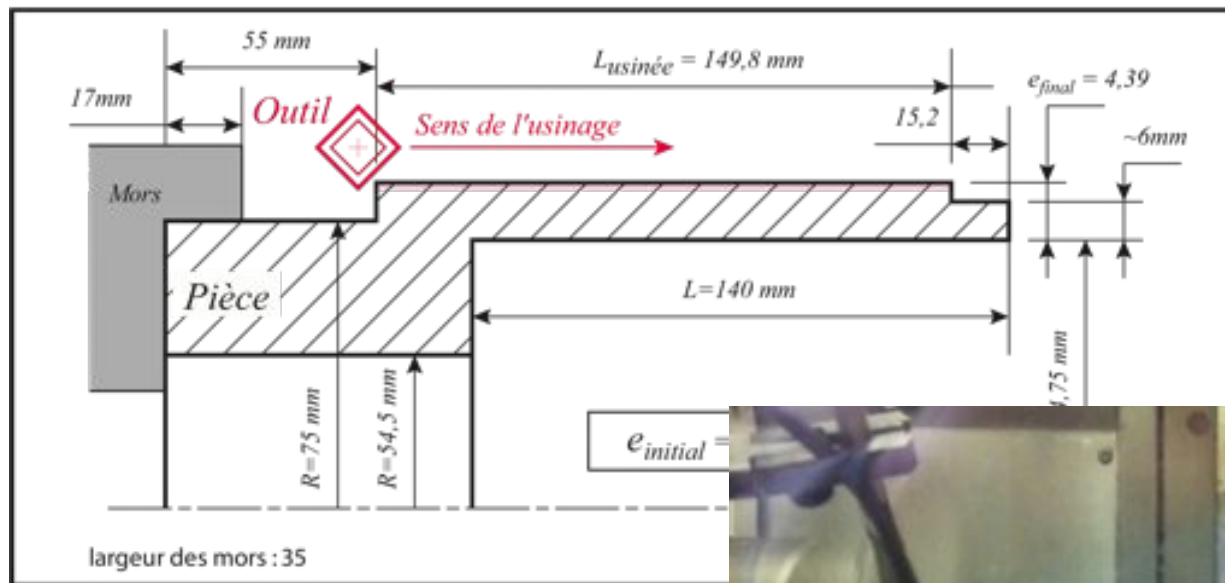
**Difficulty: We do not have data for the damping
of the tool nor the workpiece**

Simulation results



Flexible Workpiece
Rigid Tool

Axial machining of a tube

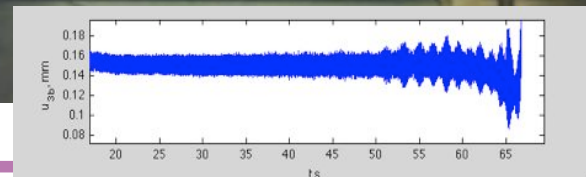
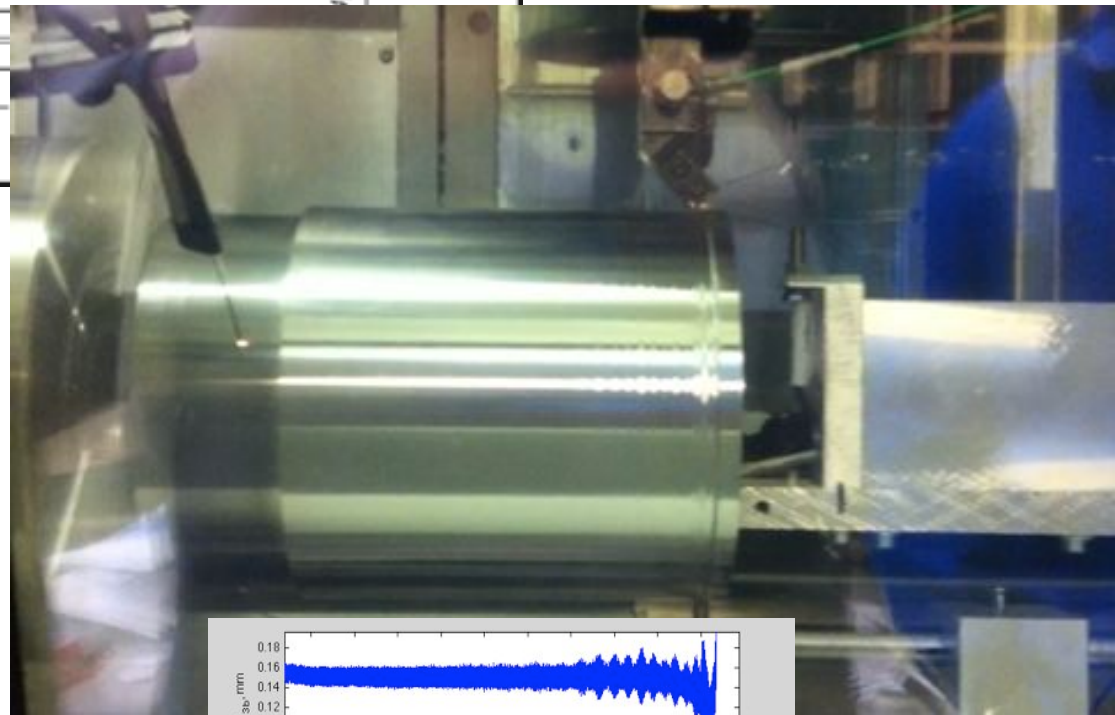


The part is the only weak component

- Regular evolution of the local stiffness

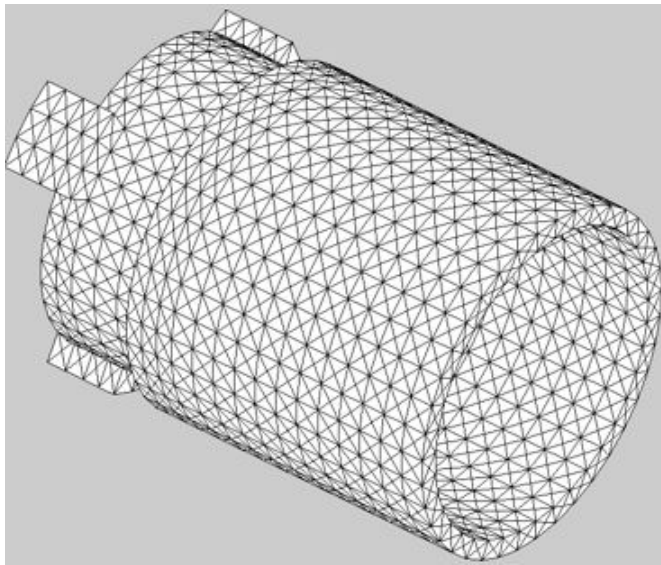


Chatter occurs during the machining

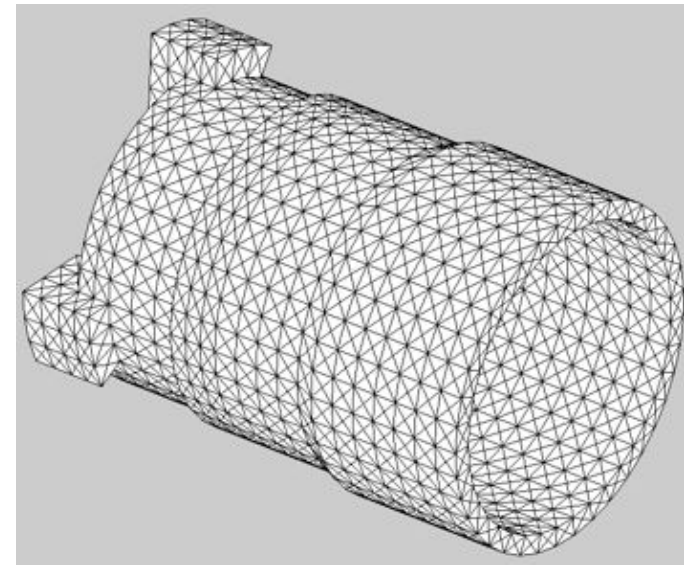


Dynamic model of the tube

The variation of the tube section is take into account with an adaptive finite element mesh



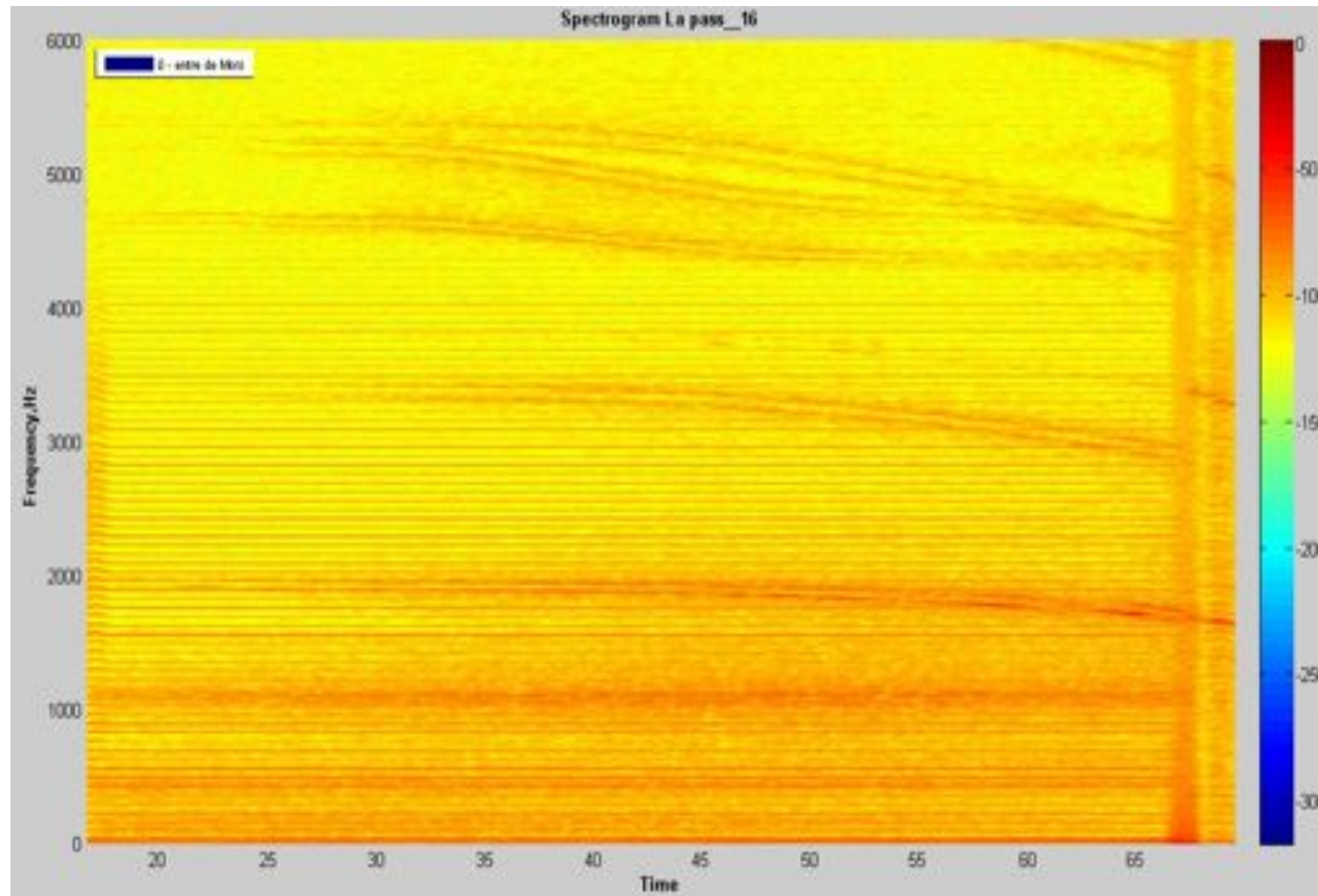
Tube before machining



Tube during machining
(tool position: 80 mm)

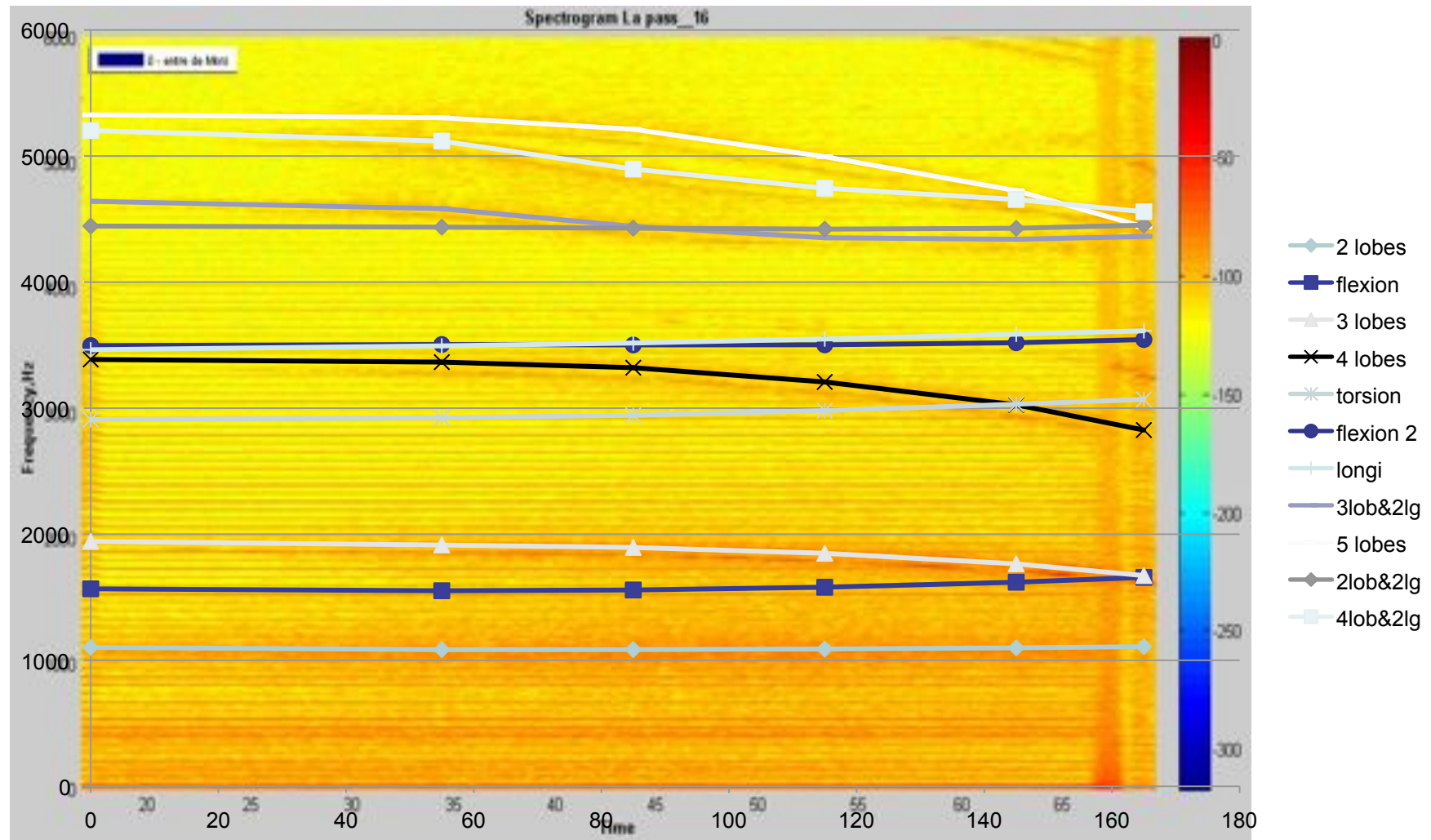
Finite Element code: OpenFEM + SDT

Dynamic behaviour of the tube: Experimental results



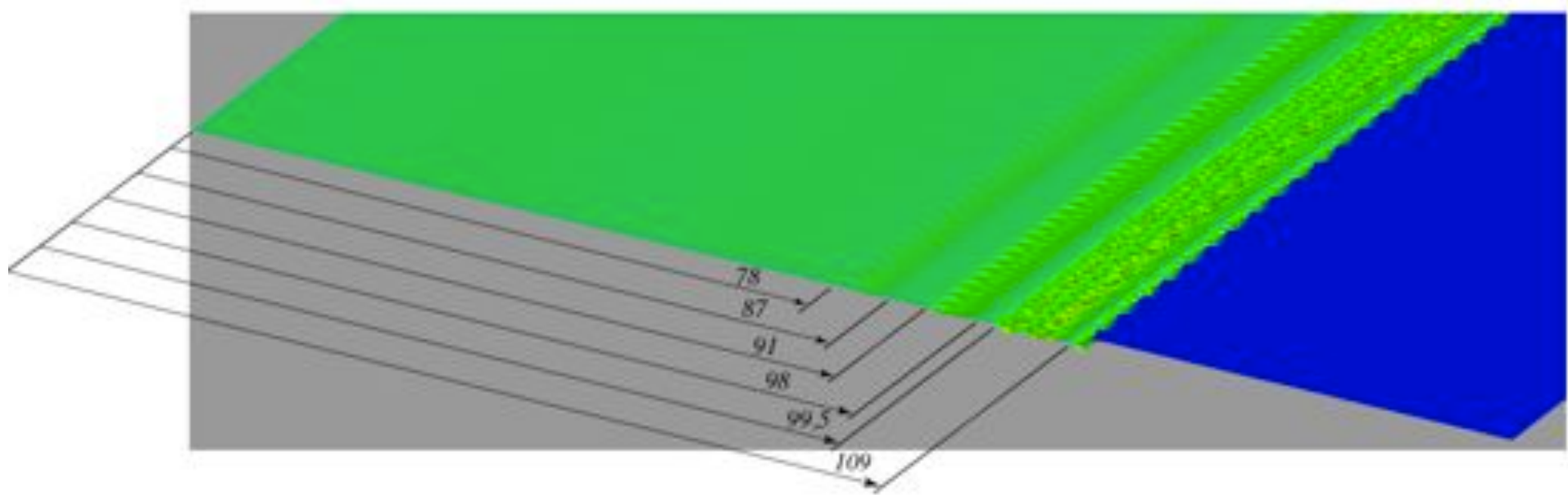
Spectrogram

Dynamic behaviour of the tube: Experimental results



Spectrogram

Simulations with evolution of the mechanical behaviour



Experimental

1st bifurcation: 90 mm
2nd bifurcation: 100 mm

Simulation

1st bifurcation: 78 mm
2nd bifurcation : 87mm

- Different vibrating zones are obtained with the time domain approach
- Ploughing is not take into account

Conclusion – Macroscopic scale

Remarks on the Time Domain approach

- Results are encouraging
- Ability to deal with industrial workpieces
- Few limitations for the improvement of the models (with highly non-linear aspects)
- Today damping modelling can only be based on measurements

Tracks to improve the results for the tube's machining simulation

- Take into account mass and stiffness evolution during machining
- Include gyroscopic effects
- Improve the cutting law (specially for small cutting thicknesses)
- Take into account the attachment
- Ploughing effect is a key point to have a realistic machining simulation for very thin workpieces

Macroscopic scale

System

Workpiece/Tool/Machine

Objectives

Machining system dynamics
Geometry of the machined surface
(form, waviness, roughness defects)
Cutting forces, power (history of ...)

Mechanical context

Nonlinear dynamics
Small strains
Known large displacement



Research at PiMM Laboratory

Milling / Turning

Flexible Part

Mesososcopic scale

System

Neighbourhood of the Tool tip

Objectives

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applied on :
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Mechanical context

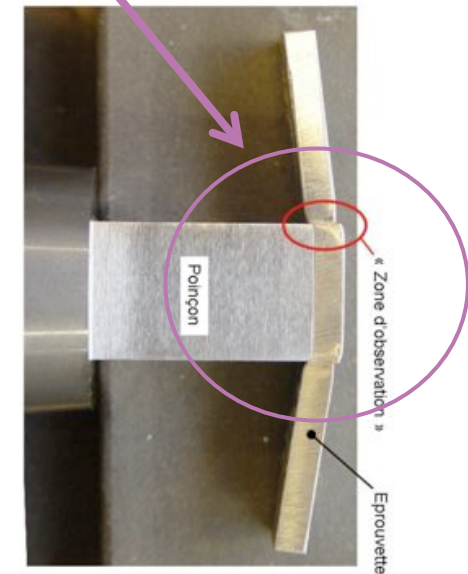
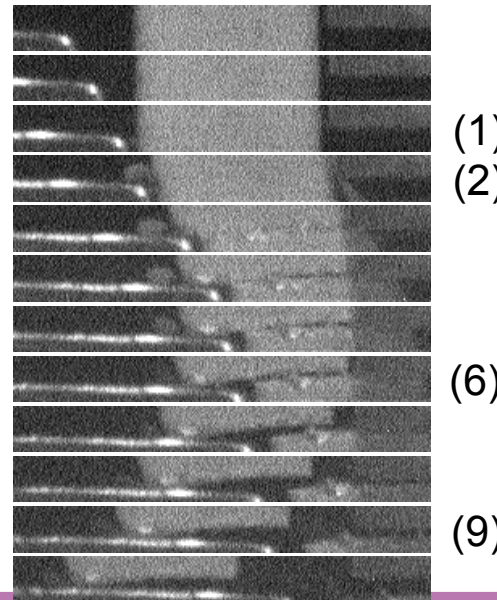
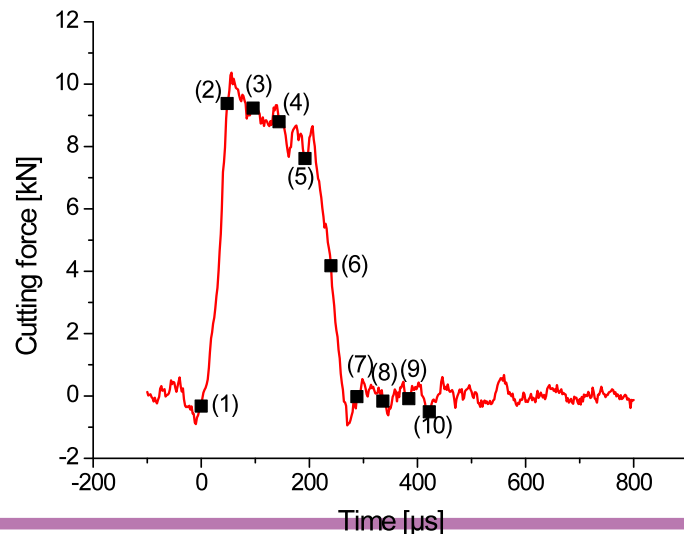
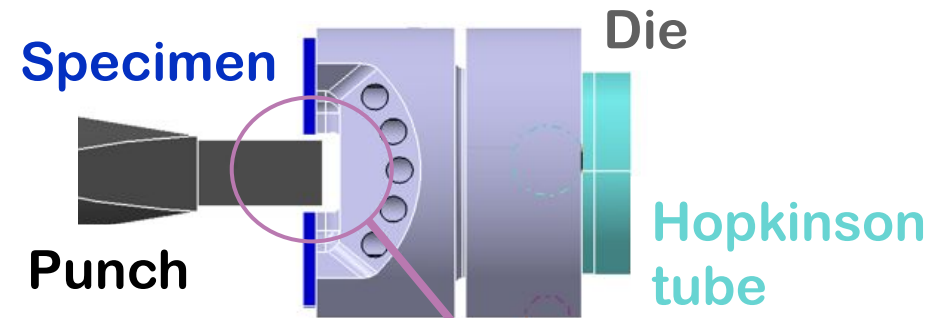
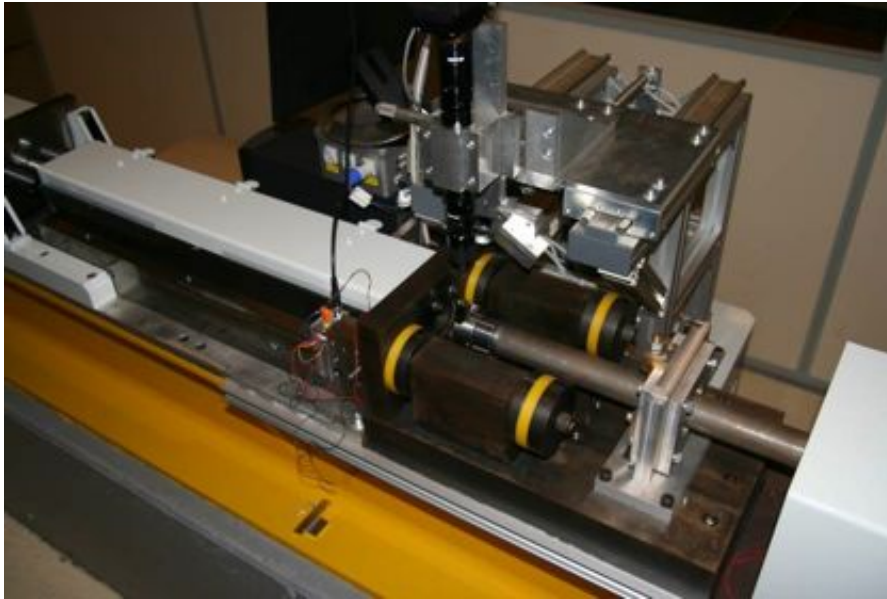
Nonlinear thermo-mechanics with
large displacement and large strains
multi-physics



Blanking / Cutting

C-Nem

Mesoscopic Scale : High speed blanking Setup



Mesosopic scale : Main difficulties

Behaviour modelling

- Constitutive law for Large strain + Large strain rates + Large temperature variation
- Tool/mater interface : High pressure / Small area / High relative speed
 - heat flux repartition ?

Handling Large strains + Large displacements

- Lagrangian FE approaches
 - Difficulties : need a regularly remeshing (and data projections)
 - Not easy in 3D for complex geometries (robustness)
- Eulerian FE approaches
 - Difficulty : boundary geometry evolution → Continuous chip only
- Arbitrary Lagrangian Eulerian approaches
 - Difficulty : how to handle grid motion for Large displacement and strains

We propose to use a new approach : the CNEM

Constrained Natural Element Method : between Meshless and FE approaches

The CNEM

Main principle : Galerkin approach base on the *Natural Neighbors interpolant* using a *Voronoi diagram* (Delaunay's dual)

$$\mathbf{u}^h(\mathbf{x}) = \sum_{i=1}^n \phi_i(\mathbf{x}) \mathbf{u}_i$$

NEM (Sambridge)
Convex domain



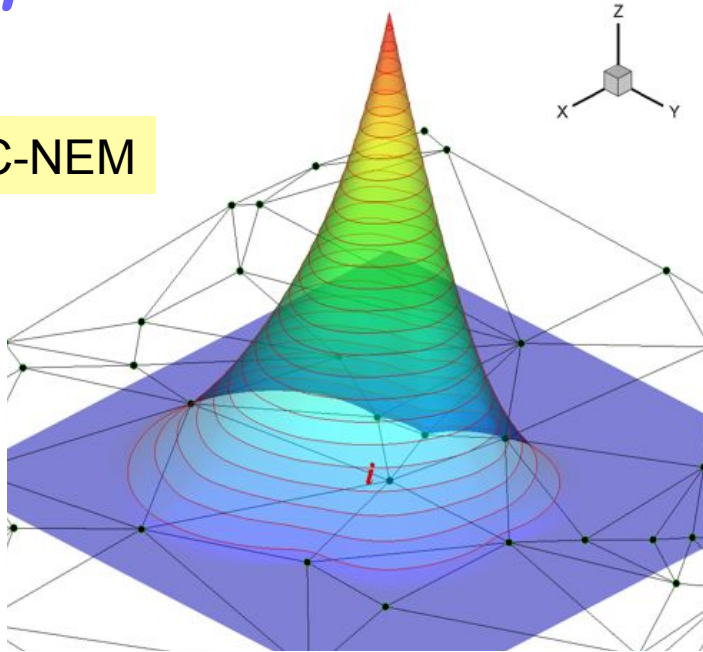
CNEM (Chinesta, Illoul, Yvonnet, Lorong)
Non convex domain : Constrained Voronoi diagram



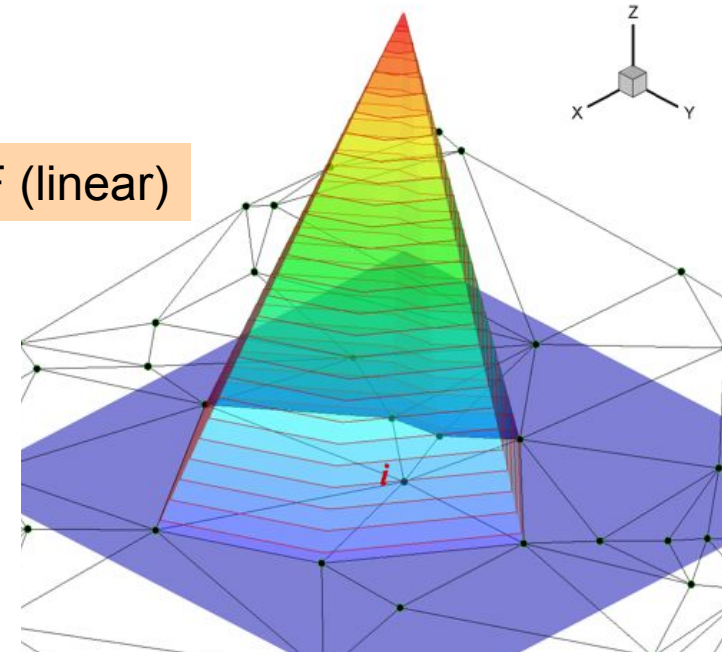
- Cloud of nodes
- Domain boundary description (tesselation)

Shape functions

C-NEM



EF (linear)



Interpolation properties

- Nodale interpolation:

$$\phi_i(\mathbf{x}_j) = \delta_{ij}$$

- Partition of the unity:

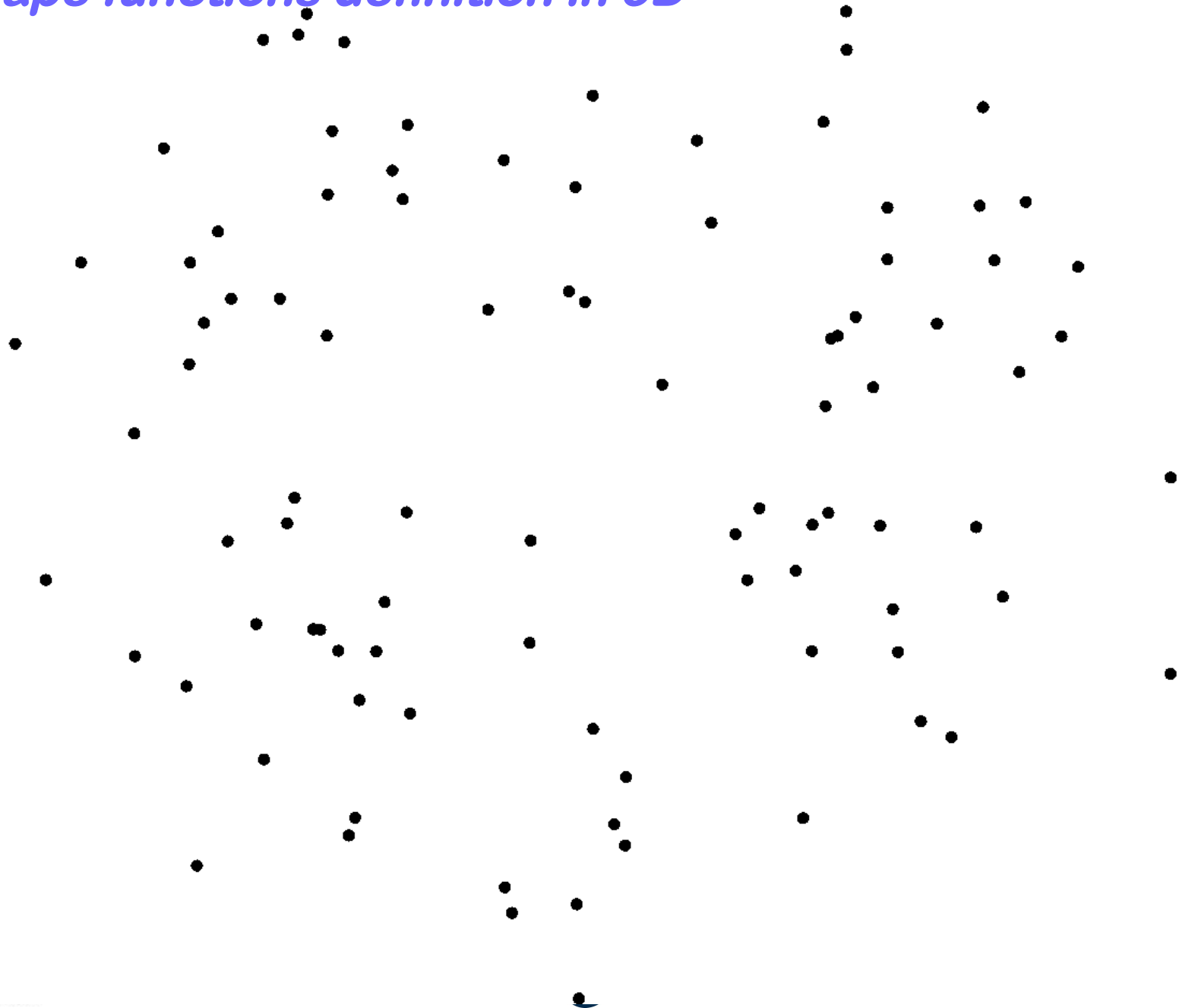
$$\sum_{i=1}^n \phi_i(\mathbf{x}) = 1 \quad \forall \mathbf{x} \in \Omega$$

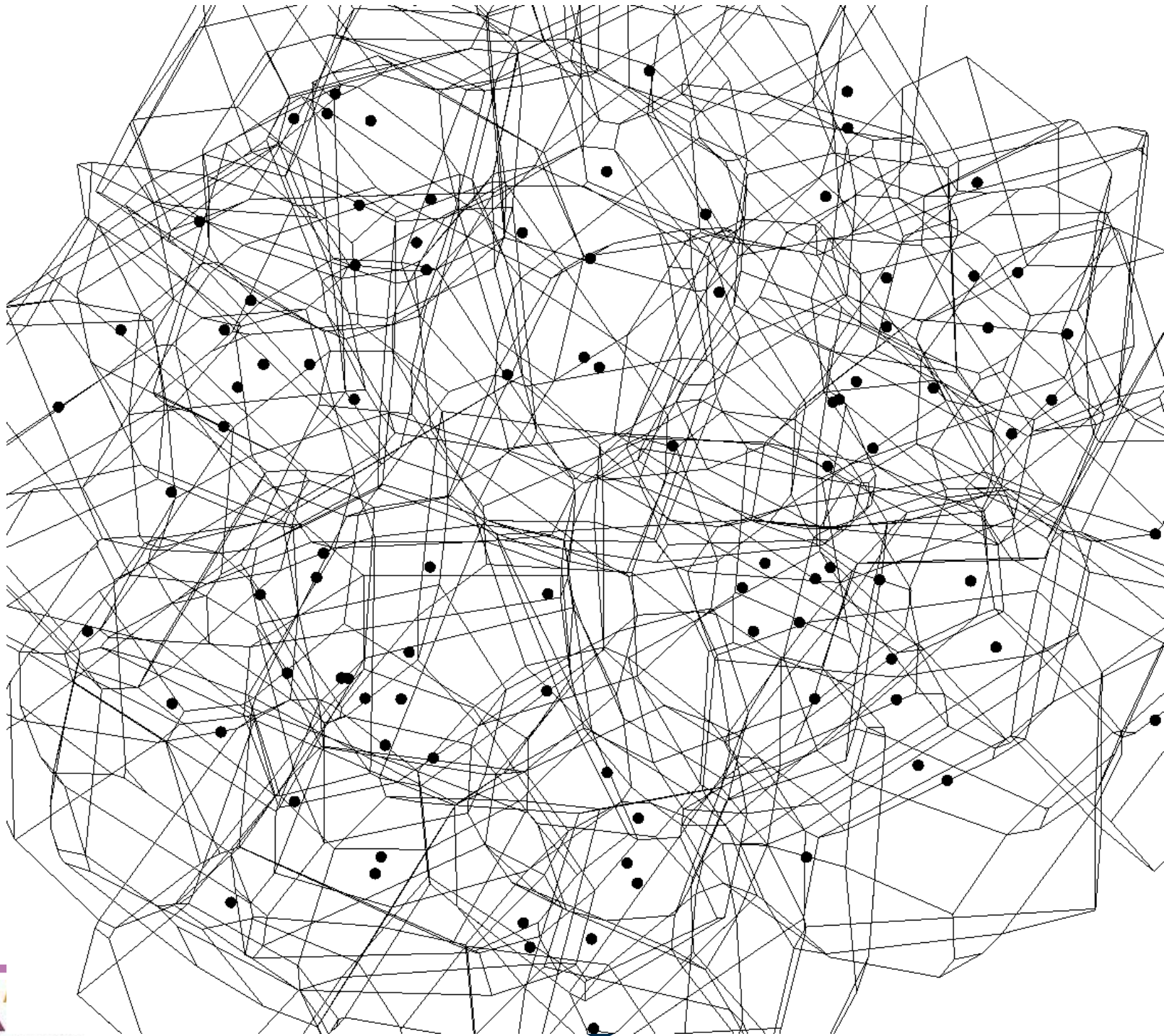
- Linear consistency :

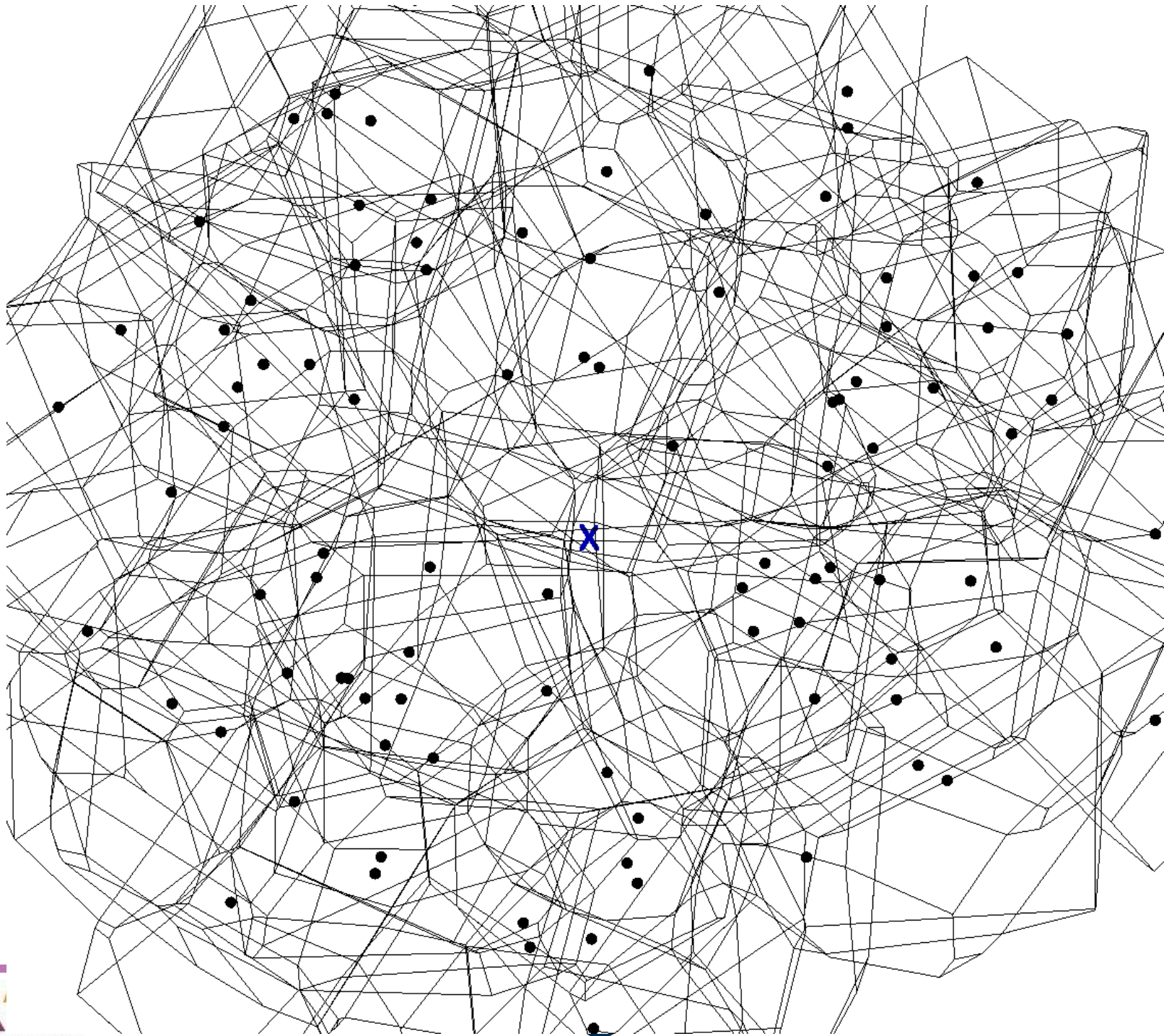
$$\mathbf{x} = \sum_{i=1}^n \phi_i(\mathbf{x}) \mathbf{x}_i$$

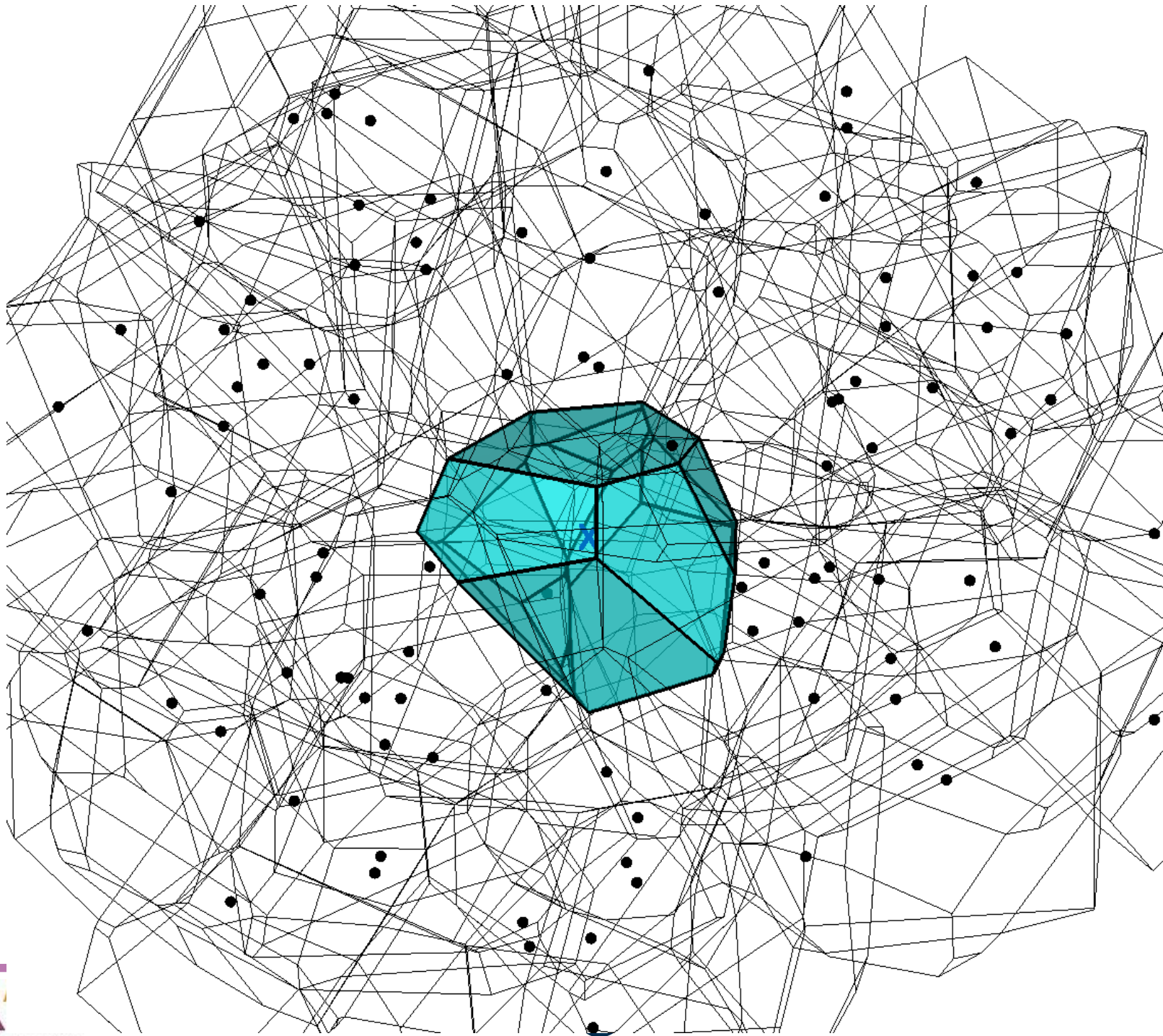
- Shape functions are local in space
- Shape functions are linear on the domain bounadare

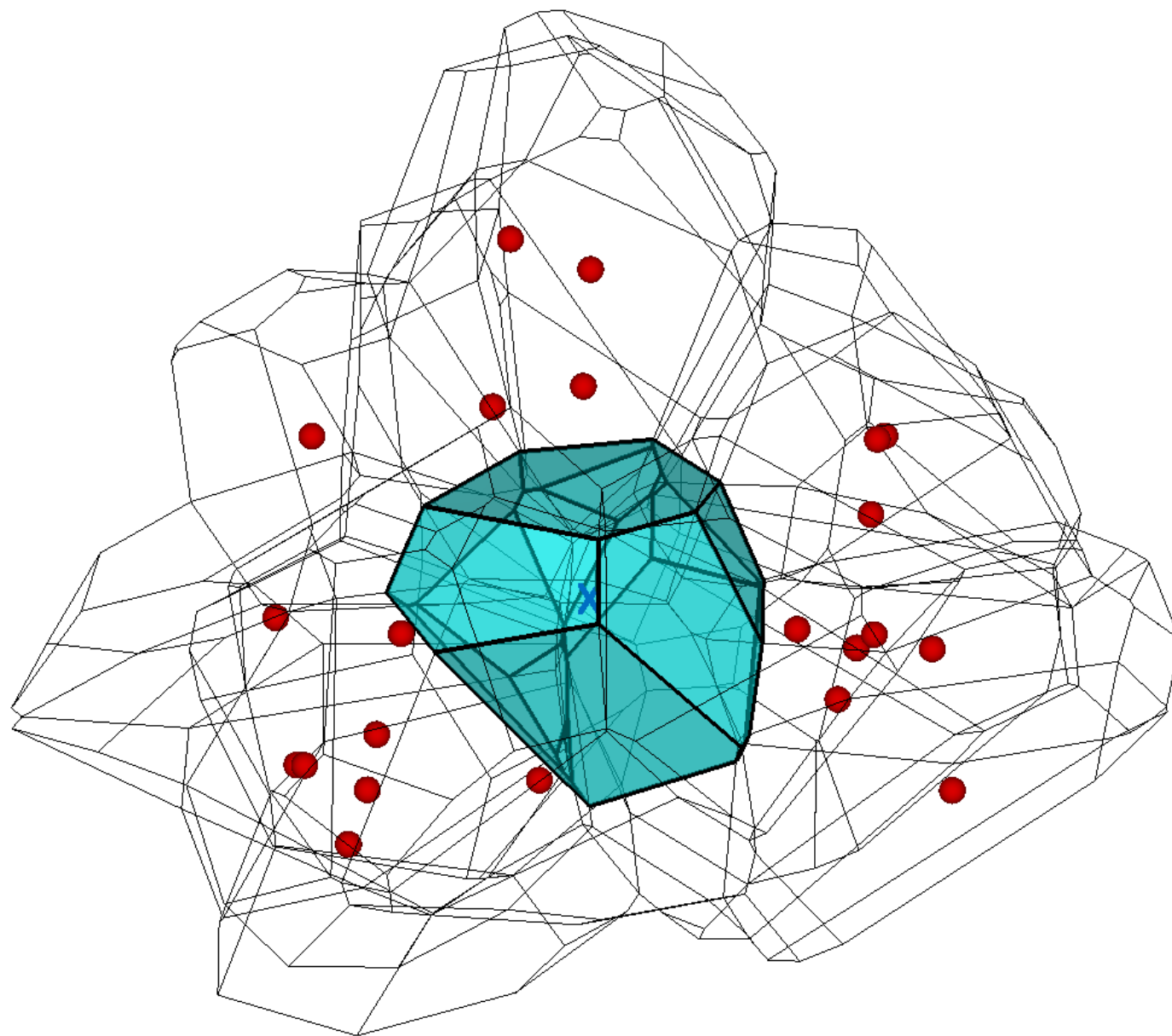
Shape functions definition in 3D

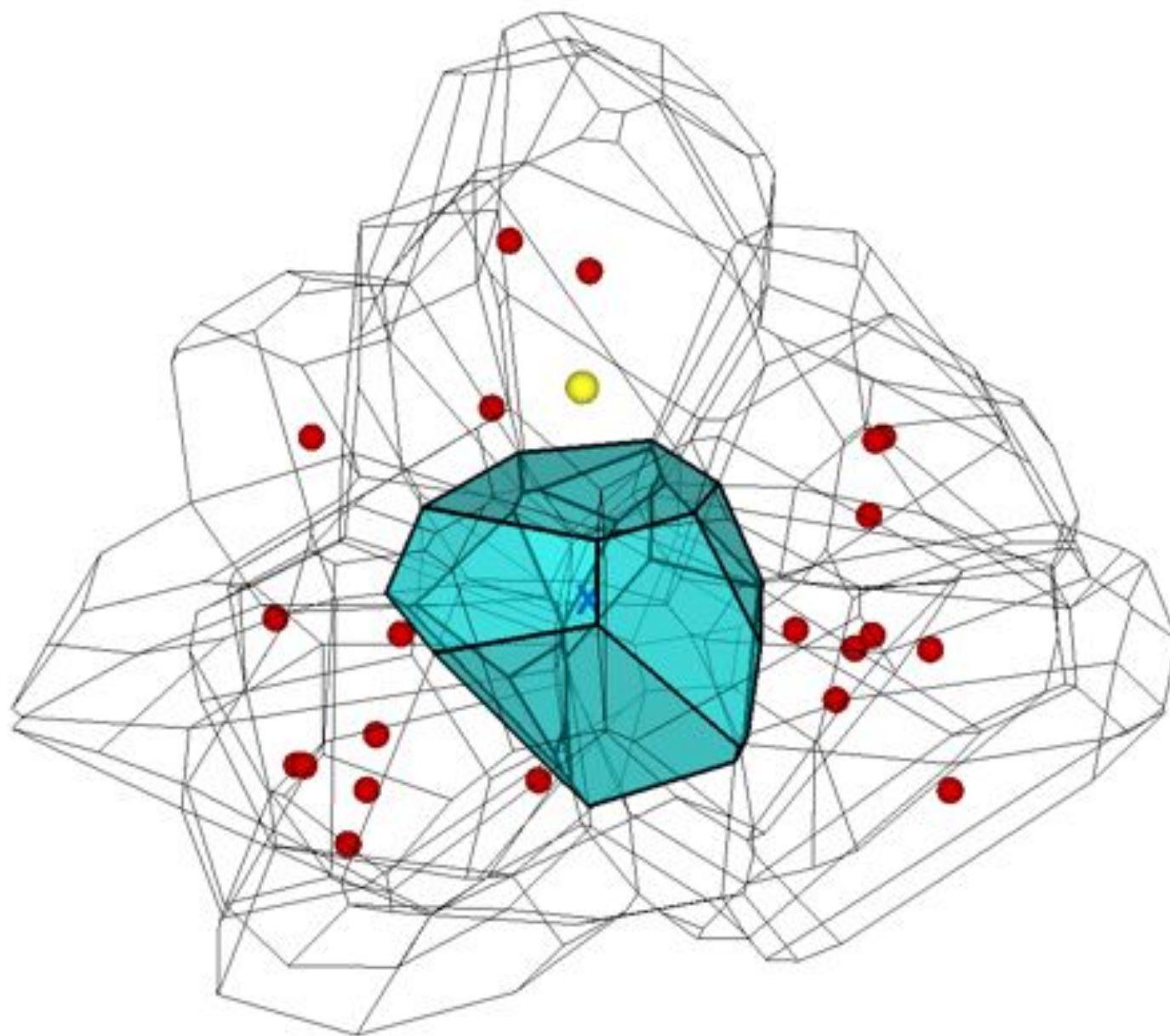


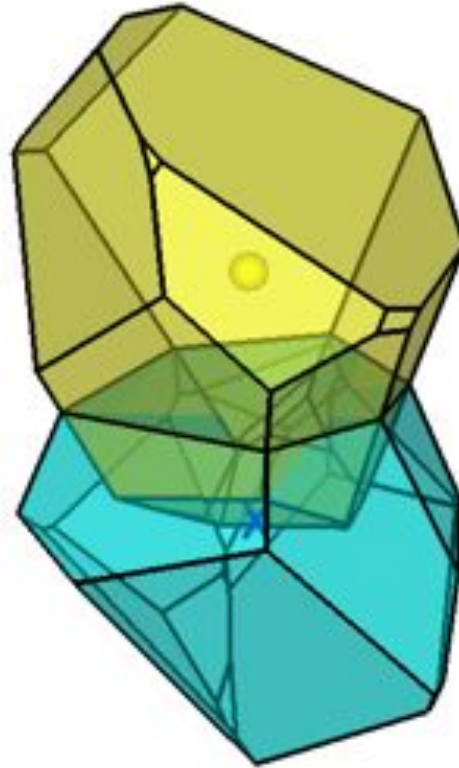


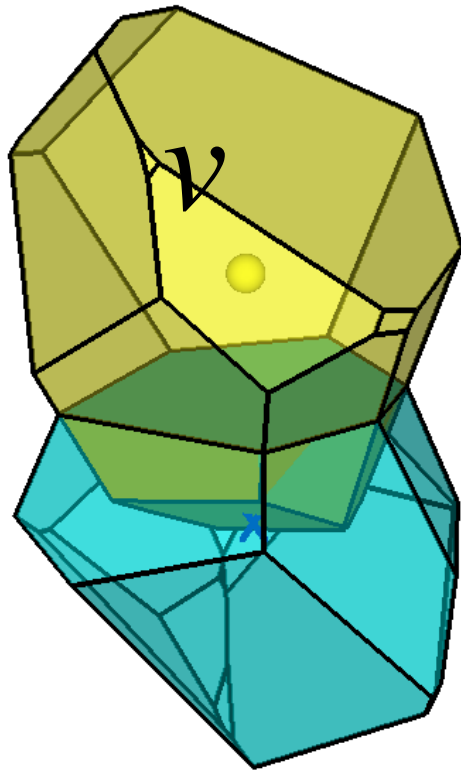












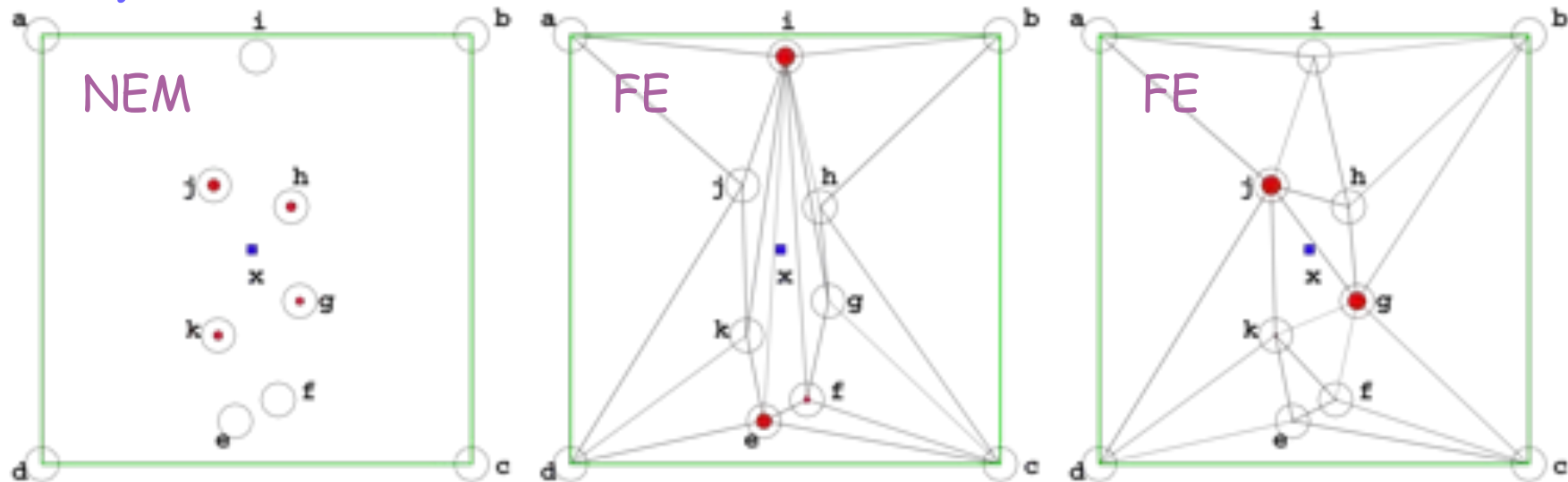
Sibson's interpolant

$$\Phi_{\nu}(x) = \frac{\| \text{green polyhedron} \|}{\| \text{green polyhedron} \| + \| \text{cyan polyhedron} \|}$$

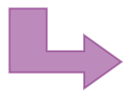
Fields interpolation :

$$\mathbf{u}^h(\mathbf{x}) = \sum_{i=1}^n \phi_i(\mathbf{x}) \mathbf{u}_i$$

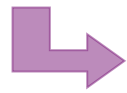
Shape functions



The quality of the CNEM interpolation :



- depends on the node density
- do not depends on the nodes respective positions



- Initial nodes can be kept during the whole simulation

Data projections are needed only when nodes are added (displacements, temperatures, plastic strains, ..)

Blanking simulation example

Specificity of the simulation

Integration scheme: Explicit

Update Lagrangian approach

Constitutive law: Johnson Cook

Thermal conduction inside the part

Die and punch are taken rigid

Example:

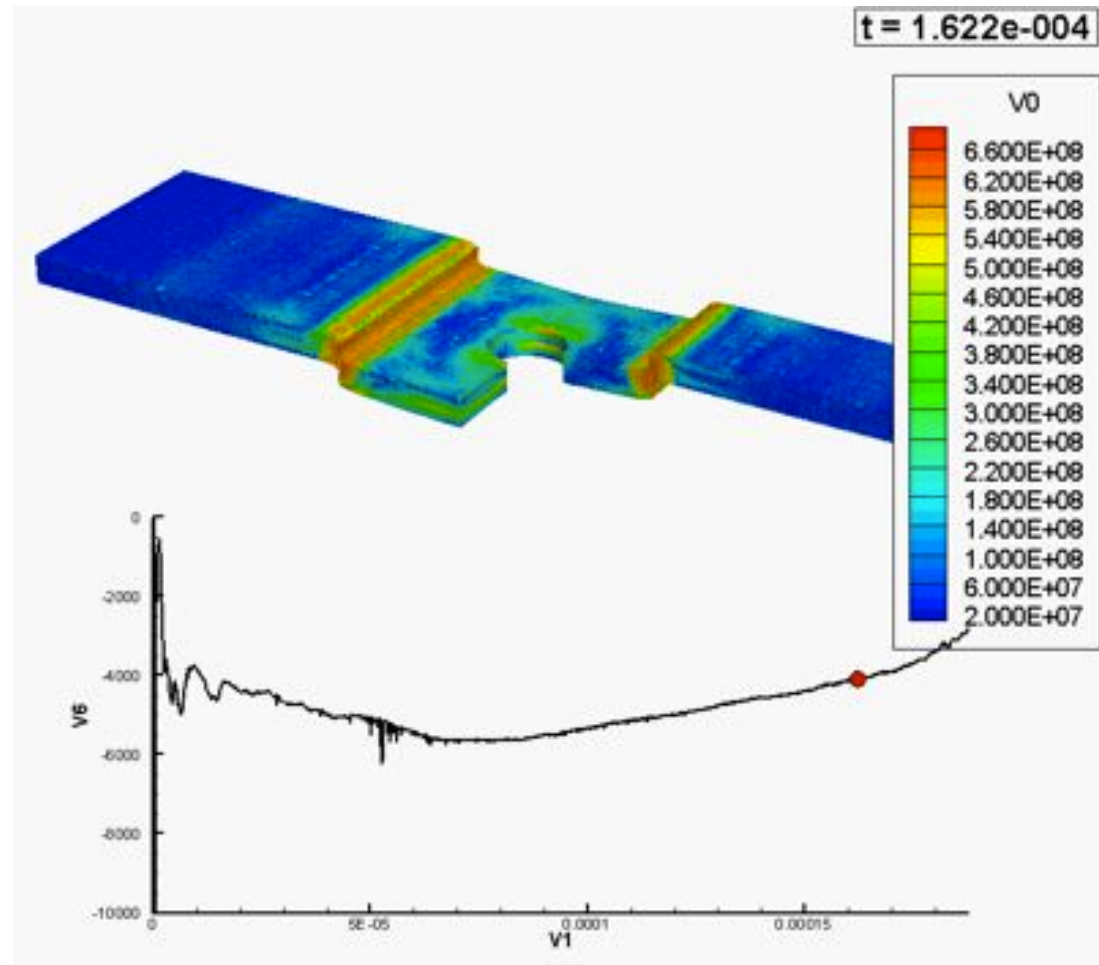
Mater: TA6V

V = 10 m/s

Lxhxe = 32x17x2mm

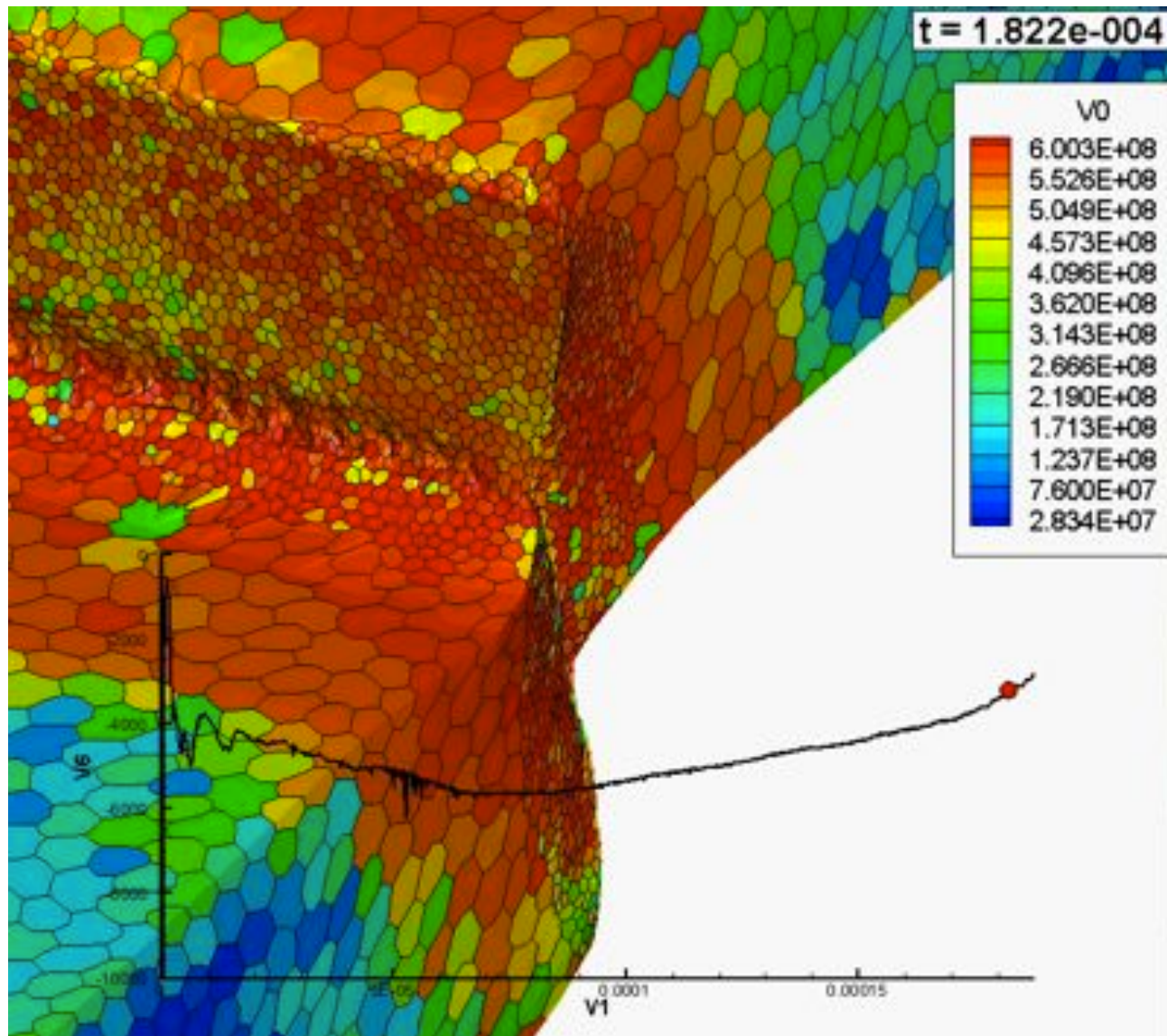
j = 0,1mm

r = 0,5mm

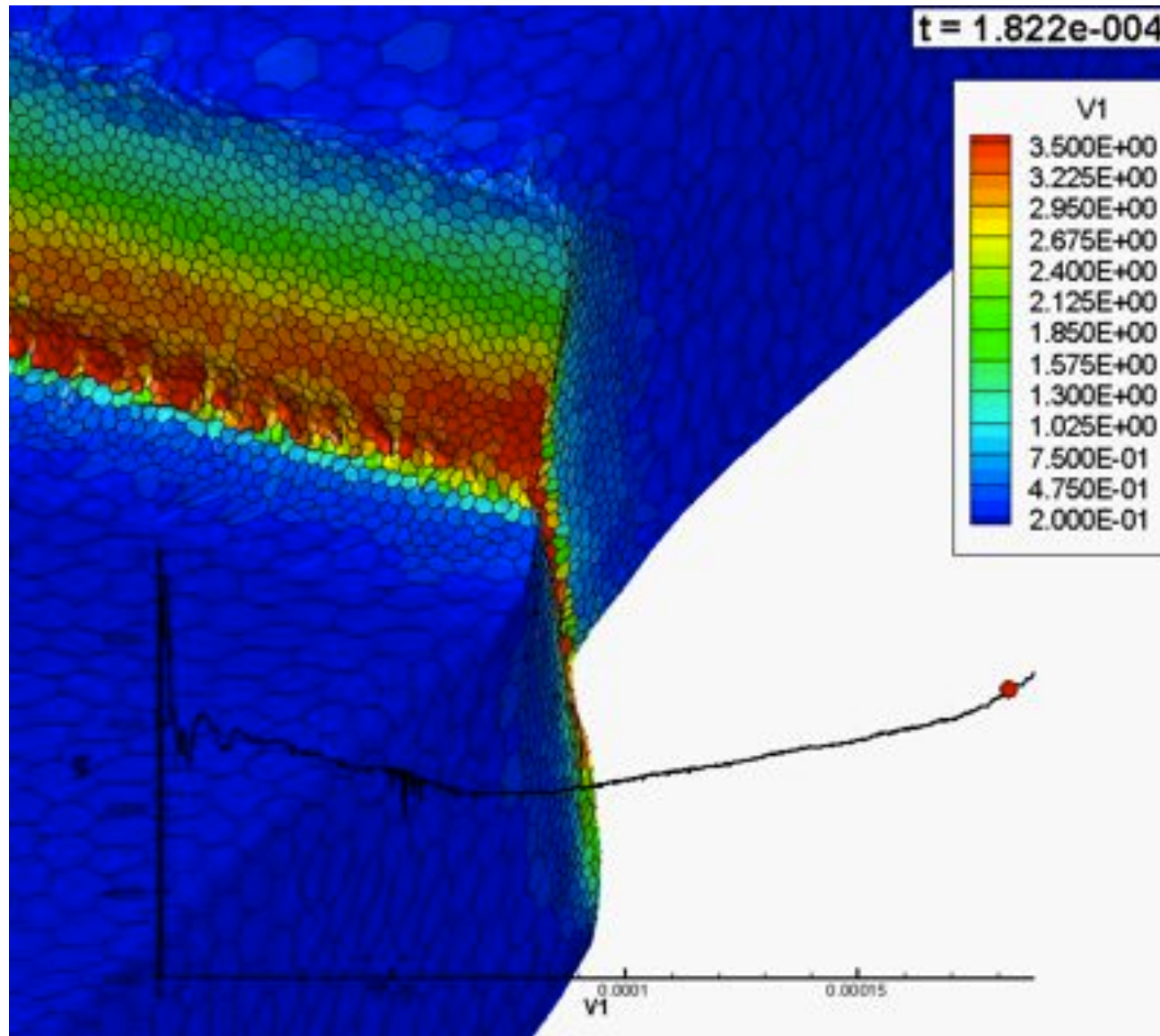


$$\sigma_y(\bar{\epsilon}^p) = [A + B(\bar{\epsilon}^p)^n] \left[1 + C \ln\left(\frac{\dot{\bar{\epsilon}}^p}{\dot{\bar{\epsilon}}_0^p}\right) \right] \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m \right]$$

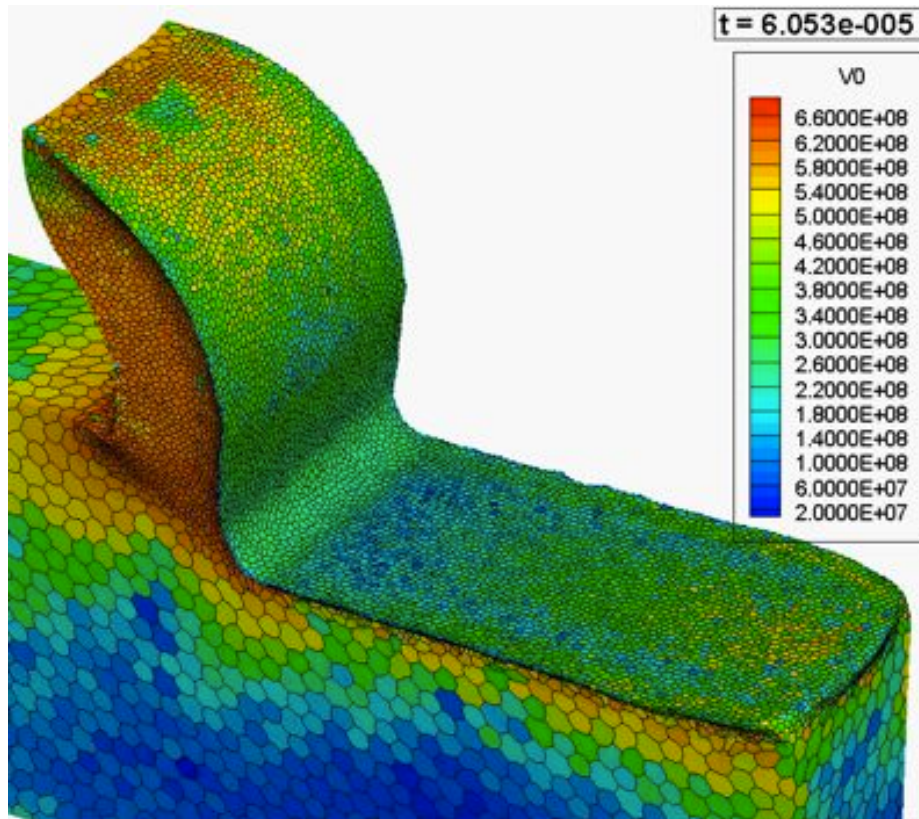
Blanking simulation example



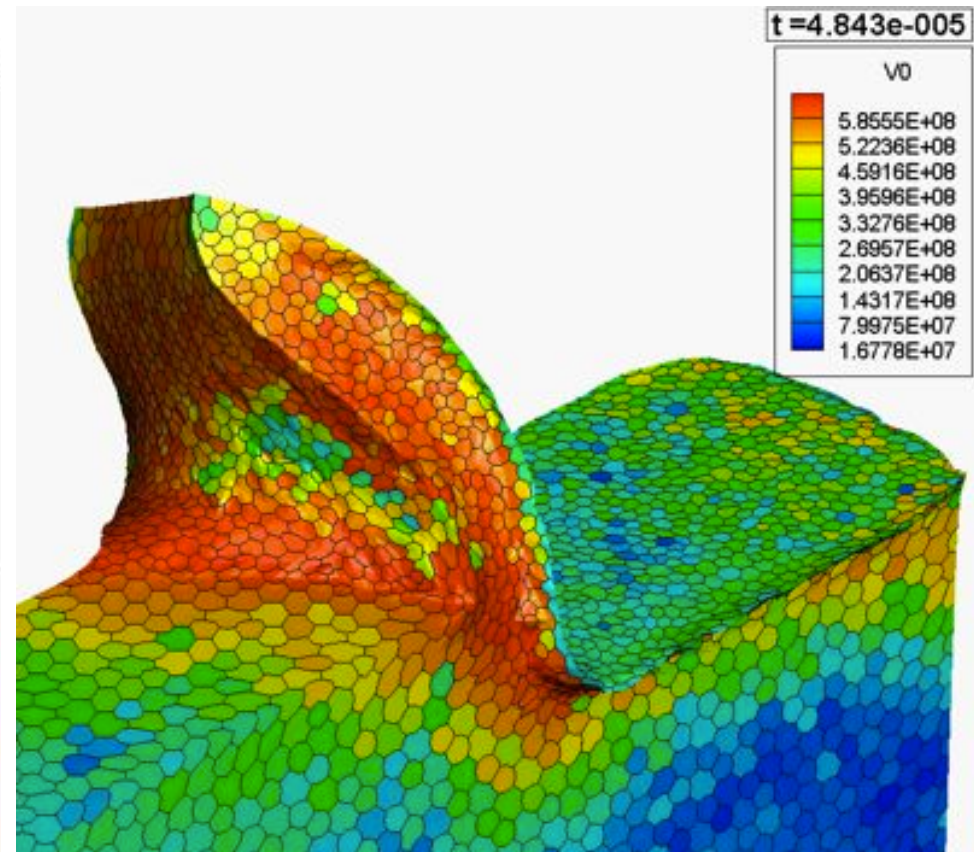
Blanking simulation example



3D Machining simulation example



Orthogonal cutting



Oblique cutting

Conclusion – Macroscopic scale

NEM/CNEM advantages:

- Update Lagrangian : position of the nodes are keeping during the configuration actualisation
→ no field's projections needed, except for new nodes
- The position of added nodes can be chose very freely

CNEM disadvantages:

- Requires a correct description (tessellation) of the domain boundary.

This description must be actualised too.

In finite transformations :

- ability of the CNEM to simulate 3d high material distortions
- the next challenge : handle mater separation and self contact

CNEM is still on work ... R